A SHORT HISTORY
OF SCIENCE

BY THE SAME AUTHOR

THE WORLD OF SCIENCE
INORGANIC AND THEORETICAL CHEMISTRY
ORGANIC CHEMISTRY
A SHORT ORGANIC CHEMISTRY
SIMPLE RESEARCH PROBLEMS IN CHEMISTRY

A SHORT HISTORY OF SCIENCE

by

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PREFACE

THE intention of this book is to show the changing attitude of men to science, and of science to the external world it studies.

The book is in no sense a work of reference; for this reason sources are not given. On p. 312, however, some hints are given to the reader in order to enable him to study more closely any part of the subject which may interest him especially.

My thanks are due to Miss E. V. Rottenburg, who ably assisted me in collecting information on numerous matters, to Mr. R. Welldon Finn, who very kindly read the manuscript and made many valuable suggestions. I am also glad to have the opportunity of expressing my obligation to Professor J. R. Partington, M.B.E., D.Sc., who was kind enough to read the proofs.

A special debt of gratitude is due to the Royal Society, and its Librarian Mr. H. W. Robinson, for permission to use the Society's Library and for leave to photograph certain illustrations which appear as Plates I, VIII and XII, and Figs. 11 and 20; also to the officials of the London Library for Plates II and XI; to the L.N.E.R. Co. for Plate XIV; and to Messrs. Watts & Co. for Fig. 4. I should also like to acknowledge my indebtedness to the officials of the British Museum, the source of most of the other illustrations.

F. S. T.

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CHAPTER I

THE BEGINNINGS OF SCIENCE

NATURAL SCIENCE

IT is not easy to define Natural Science without including or excluding more than is desirable; perhaps the following may serve to indicate what twentieth-century man conceives to be its nature.

Natural Science is the grouping of well-tested observations into an ordered and intelligible scheme, based on general Principles or Laws, discovered from such observations and capable of being used to predict future phenomena.

Under the heading of Natural Science are grouped, first the pure sciences such as Physics, Chemistry, Biology, Astronomy and Geology, secondly the applied sciences such as Engineering and Medicine; Mathematics and Logic are not to be regarded as sciences but rather as the instruments with which the sciences are constructed.

The conception of science embodied in our definition dates only from the seventeenth century; the origins of science, however, arise before the dawn of history.

CRAFTSMANSHIP AS A SOURCE OF NATURAL SCIENCE

Two of the activities of primitive man prepared the way for the building of science; these were his mastery over matter, increasing as his craftsmanship improved,

and his thoughts about the nature of the external world.

Before civilisation began or could begin man had made many notable inventions. The use of fire, the working of flint, the invention of the wheel, the making of baskets, pottery, weapons, clothing, houses and boats, and also the beginnings of the use of metal, belong to this early period. The discoverers may have been men of lofty mentality or mere favourites of fortune. Their inventions were the first crude struggles of the battle of wits against matter, the fine strategy of which is now called science.

It would seem that before about 4000 B.C. no people had advanced beyond this early stage. About this period, in Egypt and Mesopotamia and perhaps also in the Indus valley, men began to form larger and more highly organised groups and, at the same time, to progress in craftsmanship at an unprecedented rate. This progress may have been due to the increase of the size of the group allowing of specialisation in a particular type of work; perhaps the emergence of a powerful and wealthy class may have created a need for something more than the necessities of life. Whatever was the cause, crafts, arts, and the rudiments of science, developed. Slowly there appeared a differentiation between the artisan, the artist and what we may call the learned craftsman, namely the physician, architect, mathematician, astronomer, or diviner. In the activities of such craftsmen, who in Egypt at least were associated with the priestly class, we find the beginnings of science.

The invention of writing was contemporary with the beginning of civilisation in Egypt. At a very early stage (*c.* 3000 B.C.) works on some of these learned crafts were written and the elements of a recorded science were formed; certain Egyptian papyri and Assyrian clay tablets,

though much later in date, give us some idea of the nature of this early science.

MAGIC, RELIGION AND SCIENCE

Thought about the nature of the external world begins with magic, develops into religion, next reaches the level of philosophical speculation, and finally attains to the scientific method.

Man may have existed for half a million years. The relics of his early life suggest that his mental activities included something of the nature of magic or religion. No records of the thought of primitive man can be found, but the mentality of such savage tribes as have not yet been influenced by our modern civilisation affords us some knowledge of the primitive beliefs which arise in the mind of man.

It appears that magic usually precedes religion, and magic itself, as Sir J. G. Frazer has pointed out, is curiously allied to science. The savage magician does not call on a god or spiritual power to intervene on his behalf, and he may or may not believe in the existence of such powers. His rites and practices are, in his opinion, bound to bring about the desired effect, and any failure on his part is due merely to a wrong application of them. The chief "laws" on which magic is based are, of course, incorrect. The savage does not attempt to formulate them, but the ideas which underly his magical practices are probably the following:

1. *The outcome of a set of circumstances may be influenced by the representation of an event similar to the one desired.* Thus, dances representing the hunting and killing of an

animal are believed to promote the success of a similar hunt, carried out either at the same time or on some future occasion.

2. *Beings can communicate their qualities to each other by contact.* An enormous number of magical practices based on this belief are narrated in *The Golden Bough*. A simple example is the fact that in Bohemia the first apple of a young tree is often plucked and eaten by a woman who has borne many children in the belief that her fertility will be communicated to the tree, which will then bear many apples. Again, in New Zealand, an object which had been touched by the chief was thought to acquire from him a dangerous spiritual potency; so firmly did the Maoris believe that any other person who touched it would be made ill, or even be killed by it, that these effects did actually occur.

3. *Substances and persons can be influenced at a distance without any material communication in the sense of anything perceptible to the senses.* An example of this is the common practice of sticking pins into a wax figure in order to bring about the illness of the person whom it is supposed to represent. A similar practice employed by the Australian Aborigines is the placing of hot embers in the tracks of hunted animals with the object of laming them from afar and making them easier to catch.

Magic is a mistaken association of ideas. The laws of magic are not based on any accurate observations, but rather on the wish of primitive people to carry out actions which are beyond their physical powers. The lesson that the truth about material things is unaffected by our human wishes, and is independent of our sense of what is fitting, was not learned by science until the seventeenth century. Humanity in the mass may never learn it.

After magic has been supplemented or supplanted by religion, the Deity is naturally thought of as Origin and Efficient Cause of all. The sky, the sea, the rivers, the sun, are animated by the gods, and in some sense thought to be identical with them. At this stage an interest in the origin of the world usually becomes manifest, and inspires an inquiry which is perhaps the first germ of scientific theory. Since a nation has to be civilised before it can leave behind written records of its beliefs, we know nothing of the earliest and crudest notions which preceded the dawn of civilisation. We can, however, obtain some hint of the nature of these early ideas from the beliefs of savage peoples. The first explanations of the world only pushed the difficulty one stage back. Thus the Siouan family of Indians believe that their whole nation once resided in an underground village near a great subterranean lake. (They do not inquire how they came there or who created the lake and the village.) Their story is that the roots of a grape-vine grew downwards and penetrated their underground habitation. Some of the more adventurous climbed up these roots. (The difficulty of climbing a buried root does not seem to have struck them.) They saw the earth, liked it, and brought back grapes to the rest of their people. The taste of these was so attractive that all the Indians tried to climb up the vine-roots, but when about half had ascended a very fat woman broke the vine, fell back, and blocked up the access to the lower regions. At death the Siouans expect to return to the remainder of their people who are underground.

Such a simple myth as this shows the first promptings to a search for the reason why men are to be found on earth, but even a very slightly civilised people would

require some more plausible account of the beginnings of things.

FIRST SPECULATIONS OF CIVILISED MAN

The civilisations of Egypt and of Mesopotamia are by far the oldest of which we have any record. Those of China and of India are also of great antiquity. None of the early thinkers, except some of the Hindu philosophers, considered the possibility of a creation out of nothing. The possible sources of the world were either a pre-existent God, or some abstract notion such as Time or Chaos, or some material substance such as earth or water. These original sources were thought of as having existed from eternity. Thus the Babylonian cosmogony begins with the sea, and, at least in the later forms of the myth, the existence of this primal ocean was followed by the spontaneous generation of the gods, who then brought about the creation of the world. Numerous systems were to be found in Egypt. A typical myth tells us that spirit and matter existed from eternity in an intimate union. The spirit developed a longing to create. This longing resulted in a motion of the primal matter (the idea of the identity of spirit and motion is a common one in antiquity). This motion brought about the formation of the Cosmic Egg, from which emerged Rā, the God of Sun-light, who then formed the world.

All these early accounts of creation invoke the agency of a god, and have as their central theme the divine Person who creates rather than the mechanism of creation.

The Egyptians and Babylonians possessed the rudiments of scientific ability, but they did not conceive that the

creation and constitution of the world could be a matter for scientific speculation. This conception was not reached until, more than two thousand years after the greatest period of the Egyptian achievement, the Greek genius reached its zenith.

PRACTICAL SCIENCE IN EGYPT AND BABYLON

Civilisation began in Egypt at a period considerably earlier than 3500 B.C. The Mesopotamian civilisation may be of about the same antiquity. At a slightly later date, there were centres of civilisation in Persia, the Indus valley, Phœnicia and Crete.

We do not find in Egypt that the primitive culture (pp. 2, 8) of 5000 B.C. steadily and slowly improved until the conquest of Egypt by Alexander in 332 B.C. Steady progress over centuries is not the habit of the human genius. We find, rather, that a very slow development proceeded until about 3400 B.C. Then came a sudden growth and blossoming of genius, and between 3000 B.C. and 2500 B.C. almost all that was best in Egyptian architecture, craftsmanship and science came to birth. The next three thousand years, apart from the importation of Greek culture, showed an alternate decline and revival, but never the fine flower of the ancient genius. Much the same is true of the Mesopotamian culture, though here the material for study is more scanty. The dating of the Egyptian and Mesopotamian cultural periods is much as follows:

EGYPT	B.C.	MESOPOTAMIA	B.C.
Predynastic	5000–3400	Oldest remains	3500
Dynasties I—II	3400–2980	I Dynasty at Ur	2950
Old Kingdom	2980–2475	Sargon of Akkad	2725
Dark Ages			
Middle Kingdom	2160–1788	I Dynasty at Babylon	2100
		Hammurabi	2000
Dark Ages			
Empire	1580–1090	Assyrian Supremacy	1100–539
Period of Gradual Decadence		Persian Conquest	539
Persian Conquest	525	Conquest by Alexander	331
Greek Conquest	332		
Roman Conquest	30		

The Egyptians between 5000 and 3500 B.C. were between the savage and the civilised condition. They wore skins, leather, and woven linen; they baked bread and used fine pottery which, however, was not made on the potter's wheel. They used gold, silver, copper and even meteoric iron when they could obtain them, but their tools were of superbly fashioned flint. The rapid development of a civilised culture is contemporary with the invention of writing, which in Mesopotamia dates from about 3500 B.C. and in Egypt very little later. Papyrus was in use as early as 3000 B.C.

The priceless contribution of Early Egypt and Mesopotamia was the invention of the simple materials of everyday life, the things we use without a thought that they were once invented. The potter's wheel, metal tools, balances and weights, measures, chairs and tables, writing materials, perfumes, the quarrying and accurate working of stones, building technique and so forth, are inventions of the first period of human culture, the millennium before 2500 B.C. The invention of transparent glass (if not of all glass) is later and may date from about 1600 B.C.

Civilisation was rendered possible by the use of metals. Gold is found native and therefore needs no

smelting; copper and silver are also occasionally found as actual metal, while iron occurs as meteorites. These were the first metals in use, but the supply was necessarily scanty. The invention of the process of smelting metals from their ores was fundamental to the creation of a civilisation. The smelting of copper dates from a very early period, for this metal was common in Egypt in the Old Kingdom. It has been thought that its discovery originated from a primitive fashion, which became *démodé* about 3000 B.C., that of green eye-paint, made from the mineral malachite, which is a basic copper carbonate. Malachite, when heated in a strong charcoal fire, yields the metal copper. Copper ore before 1500 B.C. came from the Sinai peninsula; after that time chiefly from Cyprus. In the early period it was discovered that the addition of tin (perhaps as tin-stone) to the copper made it into a metal harder, more elastic and more easily melted; this we call bronze. The tin was scarce and valuable. Its origin is uncertain, perhaps Persia; there is no reason to believe that the Cornish mines were used as a source before *c.* 500 B.C. The imperative need for metals was probably the first stimulus to international trade, and so to exploration and the spread of culture.

The work accomplished in Egypt with copper tools was astonishing. Hard stones such as granite were cut and carved with copper chisels and saws; the copper was not apparently hardened in any special manner, but sand or emery was used to abrade the stone. The expenditure of time and labour mattered nothing to the creators of Egyptian monuments. The use of copper or bronze razors may astonish us, but cold hammering is capable of putting a very good edge on these metals.

The use of iron was exceedingly rare before 1600 B.C.;

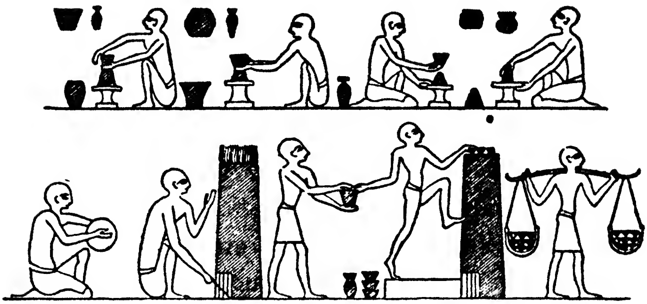

FIG. 1

Potters in Egypt, Period of the Middle Empire (*c.* 2000 B.C.). (From Erman. *Life in Ancient Egypt.* By permission of Messrs. Macmillan, Ltd.)

after that date it becomes more frequent. Homer speaks of iron as being precious in the twelfth century B.C. From 850 B.C. iron was common in Egypt and Assyria, and at about this period steel came into use. Lead was known from early times, but did not find extensive use.

The achievements of Egypt were tremendous; the means used to accomplish them were simple. There is no evidence that the Great Pyramid (*c.* 2800 B.C.) was constructed by any more elaborate means than manual labour aided by inclines, ropes and wedges: none the less its incredible accuracy of construction shows the genius of a great brain and the will of an utterly exacting task-master. Some read prophecies in its measurements: it is enough here to note with amazement that its sides, 254 yards long, differ by less than two-thirds of an inch; that its corners depart from a right angle by only twelve seconds of arc—an error of only 1 part in 27,000. Joints between the huge stones, some of which weigh 50 tons, are straight to 1/100 inch and the stones are so fitted as to be separated by only 1/50 inch of mortar. The whole was accurately orientated to the points of the compass, and the axis of

the long gallery was directed at the Dog Star at its heliacal rising. These feats imply a sound, if not extensive, knowledge of astronomy and mathematics.

The astronomy of the ancients consisted mainly in observing the position of the heavenly bodies. The Egyptians and Babylonians were not moved to this study by a curiosity about the nature of things. Their studies of the sky had two chief objects, the solution of problems connected with the calendar, and what we should to-day call astrology.

The instrument used for Egyptian observations may be compared to a fishing-rod with a hole in the handle and

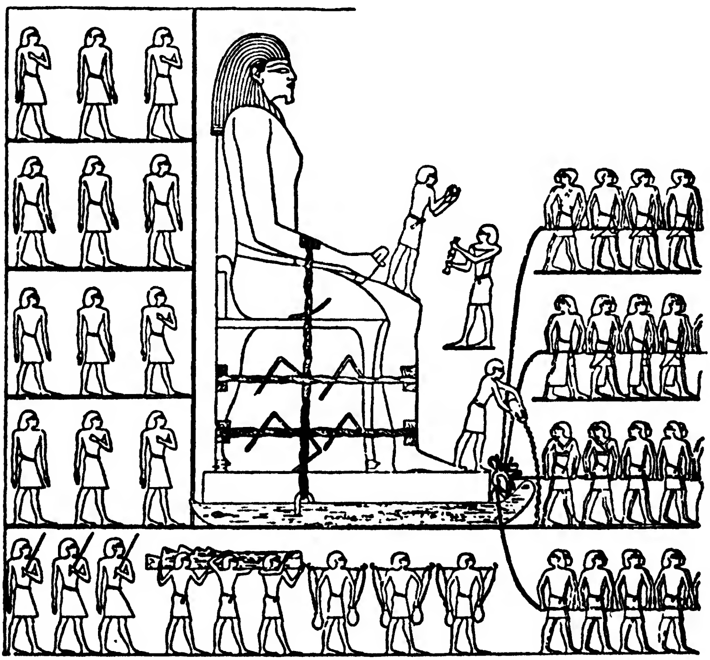

FIG. 2

Transporting a colossal Statue in ancient Egypt. (From Erman. *Life in Ancient Egypt*. By permission of Messrs. Macmillan, Ltd.)

having a plummet attached to the line instead of a hook. The apparatus was adjusted so that the observer, looking through the hole, saw the line coincide with the pole star. The apparatus was then known to be accurately orientated north and south, and the position of stars relative to the vertical line could be mapped out. The apparatus also served to tell the time during the night. Careful observation of the stars was needed to discover the length of the year and establish a calendar. The length of the year is now known to be 365 days, 5 hours, 48 seconds, or nearly 365¼ days. The first recorded estimate of the year's length was 365 days. This was adopted by the Egyptians at an early period, with the result that every Egyptian year started ¼ day earlier than it should. Just as a clock which continually gains eventually comes right again, so the accumulation of these ¼ days in the course of 1460 true years added up to a whole year; so that in 1460 years the fixed festivals shifted through spring, summer, autumn and winter and back to spring again. This was recognised at least by the late Egyptians; for they knew that the Dog Star had risen heliacally on the first of the month of Thoth in A.D. 138 and in 1322 B.C. It is very tempting to assume that they knew this had happened also in 2782 B.C., but it is doubtful if the temple records, which were certainly kept, went back so far.

Babylonian astronomy was chiefly astrological. The inhabitants of Mesopotamia were star-worshippers as early as the Sumerian period, *c.* 3000 B.C., and the pseudo-science of astrology may date therefrom. The whole religious life of the people was centred on the heavenly bodies. The gods were identified with the seven heavenly bodies—sun, moon and five planets—and

the fortunes of the nations were predicted by the astrologers, whose writings have survived on clay tablets. Eclipses were studied with anxious care, for in these the sun- or moon-god suffered diminution and darkness. It was early realised that eclipses could take place only at full-moon. A much greater discovery, which must have had tremendous import for the priest-astronomers, was the prediction of eclipses. It is now known that the periods of revolution of the sun and moon with respect to the earth are both submultiples of 223 lunations, which amount to 18 years and 11 days. Accordingly at the end of such a period sun and moon return to the apparent positions they held at its beginning and eclipses recur at such an interval. The Babylonians by their observations discovered this period, which they called a *saros*.

Many and accurate astronomical observations were made by the Babylonians and Egyptians, but we must not assume that they had any thought that the stars or planets were worlds, though the Babylonians realised they were vastly distant. Both peoples seem to have arrived at the notion of the universe being a closed space, floored by the earth and roofed by the sky, which was thought to be a definite material boundary. The notion of a closed and finite cosmos remained general until the seventeenth century.

The mathematics of the ancients seem to us clumsy: we have been brought up in an atmosphere of arithmetic and forget that the multiplication table is but a few hundred years old. The earliest known work on mathematics shows a huge advance on the simple counting of savages; it is a papyrus, copied about 1550 B.C., but describing operations which may date back to the Old Kingdom. Its author, Ahmes, used a decimal notation, but since the

zero was not yet invented he had to use different signs for 1, 10, 100, 1000, 10,000, etc. The ordinary modern arithmetical methods could not be used, just as they cannot with Roman figures. The Egyptian could add and subtract; he could multiply or divide by 2, 5, 10, or $1\frac{1}{2}$. He could not multiply by other numbers. Thus to multiply 120 by 18 he would double the former number four times in succession—120, 240, 480, 960, 1920. To the last figure he would add twice the number and the result 1920 plus 240, i.e. 2160 would be the answer required. Fractions were well understood, but the numerator (except in the case of 2/3) had to be one. Problems of the simple proportion type, and also some which we now attack by simple algebraic equations, could be solved.

The practical needs of architecture and surveying called for the elements of geometry, and this made no little progress. Areas and volumes were fairly accurately computed. Egyptian geometry, however, came to little more than a practical means of calculating distances, areas and volumes. There is no reason to suppose that the Egyptian geometers had any interest in the properties of geometrical figures, still less that they attempted to find logical proofs for their constructions. Both logic and an interest in pure knowledge were introductions of the utterly novel genius of Classical Greece.

Babylonian arithmetic was well advanced. Their scale was sexagesimal; that is to say, it was based on the number 60, as ours is on the number 10. Their notation, too, like ours and unlike that of the Egyptians, depended on the position of the symbols. Thus the number 67 could be represented as 1.7, and the number 3781 (which can be expressed as $60^2+(3\times60)+1$) would appear in the form 1.3.1. There exists a clay tablet with a correct

table of squares from 1^2 to 60^2, and another which indicates some knowledge of arithmetical and geometrical progressions.

The science of Biology does not exist before the time of Aristotle (4th century B.C.), but the arts of medicine and surgery have existed from the remotest eras. Throughout its history medicine has employed, though not always consciously, two main types of therapy, namely, the influencing of the body by the mind, and the influencing of the body by physical remedies; nor have these methods been mutually exclusive.

The earliest medical treatise is the document known as the Edwin Smith Surgical Papyrus, which was copied some 3600 years ago, but contains matter which was probably first written in the great age of Egypt, 3000–2500 B.C. At that period it would seem that the physician held a higher position than any other learned craftsman, and the palace-physician, known as the "Physician of the Belly" or "Guardian of the Anus" was an important official. It is clear that the practitioner who composed this particular treatise was a keen observer and a skilled surgeon, one who relied on his art and not on the aid of faith or magic. The original treatise evidently dealt with all surgery, starting from the top of the head and ending at the foot, but unfortunately our copy is but a fragment and treats only of the head, neck and chest. The author understands the treatment of fractures by splints and the reduction of dislocations and the stitching of wounds; he has, moreover, a very shrewd power of predicting the course of an ailment. Ancient physicians did not care to treat incurable diseases, for the patient's death was too often ascribed to medical ministrations. Accordingly the method of our author is first to describe a set of symptoms: then, if he

believes the ailment to be curable, he instructs his reader to say, "I will treat the ailment." If, on the other hand, he regards the symptoms as indicating a speedy fatal result he advises him to say, "I will not treat the ailment." Thus he describes the symptoms of an uncomplicated broken nose and recommends a practical and efficient treatment, consisting of cleaning and plugging the nostrils and splinting the nose by means of rolls of linen bandaged on to each side of it. If, however, the patient had not only a broken nose but also the symptoms of bleeding from the ear, pain on moving the jaw, and aphasia, our surgeon will not touch the case; for he knows it will prove fatal. He is here well-advised, for these symptoms might point to a fracture of the base of the skull. The treatise is an admirable scientific work; we do not find its like in the two thousand years between its probable origin and the works attributed to the Greek physician Hippocrates (*c.* 450 B.C.).

It is fascinating to speculate that the author of this treatise may have been the half-legendary Imhotep, of whom we learn that he was vizier to king Zoser (for whom he built the step-pyramid) and was wise in the arts of magic, medicine and architecture. Imhotep was made a demigod soon after his death and late in Egyptian history was made a full god—patron of the healing arts; in Egypt such an honour was very rarely awarded to any human being.

The next Egyptian medical document, the Papyrus Ebers, was written about 1550 B.C. though its matter is older. It compares but poorly with the Surgical Papyrus, being unsystematically arranged and showing little observation. Some of the drugs used would be effective, but most of them are complex messes of animal and vegetable ingredients. The free use of dung must have done more harm than good, and a poultice of raw egg and goose-

guts, designed to cool the anus, is at least alarming. The papyrus, however, names a hundred or more ailments, and shows that very many drugs were available. We should not be surprised to find that many of these are useless, for the testing of the efficacy of drugs is exceedingly difficult. It would be rash to say that all the drugs in use to-day have valuable therapeutic effects.

Babylonian medicine was even less modern than the Egyptian. Some fairly effective preparations were employed, but these were always accompanied by spells, of the use of magical amulets, or the magical transference of diseases from the patient to animals. No doubt, the mind of the patient was powerfully influenced and the healing powers of the body were aided, but the contribution to scientific medicine was of the smallest.

The contribution of Egypt and Mesopotamia to science was, then, the invention of practical arts allied to science. We must wholly reject the idea of a steady progress towards this end. Rather should we visualise a great wave of invention and of mental and physical activity arising in the period round 3000 B.C. and lifting the ancient cultures to a level from which, during the succeeding 2500 years, they on the whole declined. But even in the worst periods of decadence, the practical arts, which were a part of the life of the people, survived. World-trade, as it grew, diffused these arts to other centres and gave the whole civilised world a new level of cultural life from which the next advance could spring.

The next wave of human endeavour towards knowledge gathered strength in the centuries following 700 B.C., when in India, China, and especially in Greece, achievements were reached which in many ways have never been surpassed.

CHAPTER II

THE SCIENCE OF GREECE

THE GREEK PHILOSOPHERS

THE beginnings of the Greek culture arose in the island of Crete at a period not far distant from 2000 B.C. The Cretan civilisation was based on sea-power and naturally threw off colonies, chief of which was Mycenæ in the Peloponnese. In the twelfth century B.C. Greece was overwhelmed by invasions from the north and for centuries we hear little of culture. The Greek has always been a trader and a colonist; in the eighth, seventh and sixth centuries B.C., wine, oil and textiles were made and exported, and the profits of trade relieved the struggle of life sufficiently to let the many live and the few think. A period followed which in art, literature and philosophy has never been surpassed.

Rational science arose out of the Greek culture, though not in Greece itself, for the earliest natural philosophers, who lived in the seventh and sixth centuries B.C., dwelt in the Greek colonies in Asia Minor. From the fifth century, Athens became the centre of scientific thought; after the foundation of Alexandria in 332 B.C. Greek scientific culture, a little altered in spirit, continued its triumphs in that city. After *c.* A.D. 200 a decline set in and the Greek genius slowly became sterile. In A.D. 640 the Arabs overran Egypt, but the Greek science still remained in Byzantium, and there continued as an academic study until the fifteenth century. The Greek scientific culture

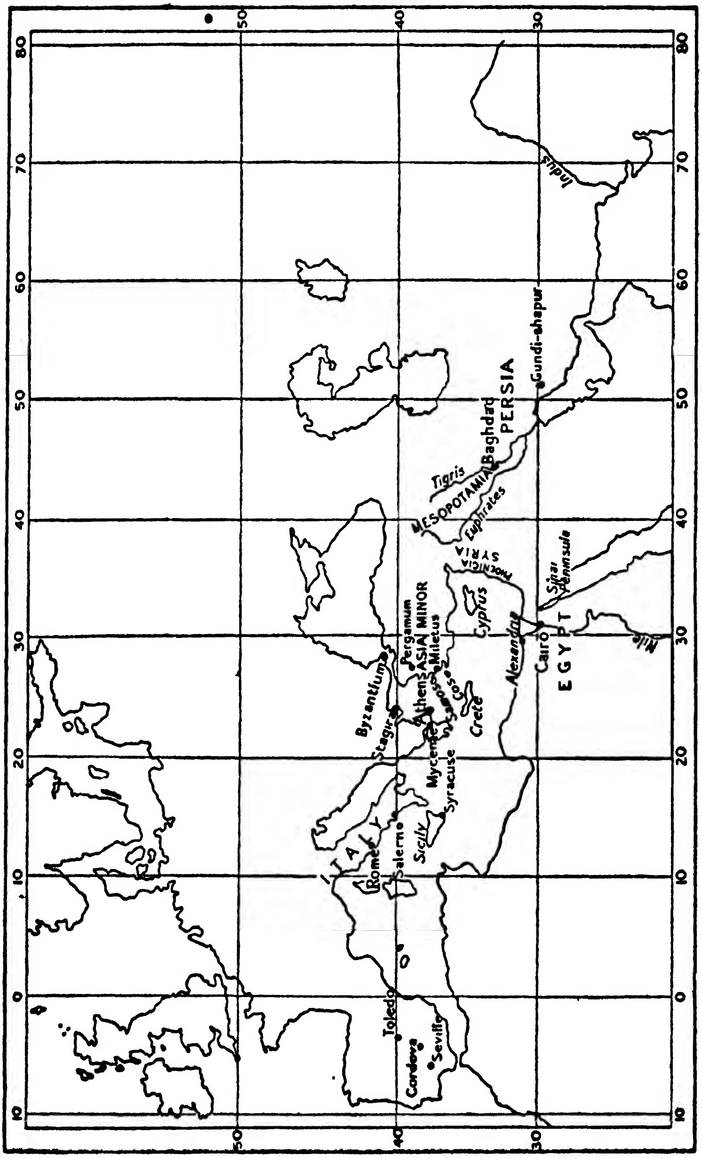

FIG. 3
Map, showing centres of scientific culture before 1000 A.D.

had nearly a thousand years of active life, and nearly a thousand years of sterile preservation. Nor was its day then over; for in the fifteenth and sixteenth centuries, Europe became acquainted again with Greek science, the inspiration of which helped to arouse the spirit of inquiry which lies at the root of modern scientific ideas.

The culture which arose in Greek-speaking lands from the seventh century B.C. onward was marked by a new feature, the desire to know for the sake of knowledge. Egyptian and Babylonian science was for use; by its aid land was measured, eclipses were predicted, wounds were healed. But the Greeks scorned the practical motive for inquiry. Anaxagoras, when asked for what end he had been born, replied, "For the contemplation of the sun, moon, and heaven." Euclid, when asked by a young man what good he would get by studying geometry, told a slave to give him sixpence, since he needed to be paid to learn. This passion for pure inquiry as apart from its application to common life was the strength and weakness of Greek science. Any dealing with material things was felt to be unworthy of a philosopher. Crafts, and to some extent the arts also, were work for slaves: to concern himself with such matters as tanning, glass-making or metallurgy argued a base and servile disposition in a philosopher. For this reason chemistry made no progress among the classical Greeks. Mechanics and engineering fared little better. Archimedes in the third century B.C. invented a great number of mechanical contrivances, but disdained to write a book on what he considered to be merely the playthings of philosophy (p. 55). But the world at this period needed free inquiry, and the development of systematic reasoning and logic, far more than it needed the experimentalist. The seventh century B.C. is

the greatest landmark in the world's history, because at that date Man began the building up of a systematic method of argument, so designed that anyone who read it would either be compelled to agree with the writer or would be able to compel others to recognise the latter's conclusions to be false. The development of logical reasoning led to the possibility of accumulating established and incontrovertible knowledge; this, which is one of the essentials of science, is the chief contribution of Greece.

It is interesting to ask why the Greeks made this radical departure from earlier modes of human thought. As part cause racial characteristics may be invoked; in part it was due to the nature of Greek religious beliefs. Egyptian and Babylonian science was in the hands of a priesthood, and, for that reason, such ultimate questions as the creation of the universe, the nature of the heavenly bodies and the illnesses of man were unlikely to be explained except in terms of the influence of personal spiritual forces. The Greeks were the most tolerant of nations and religion wielded but little political influence. It was therefore possible freely to pursue ultimate questions without exciting the horror of the pious; for the first time in the world's history, there was free and rational inquiry into the nature of the universe, the gods, and the soul of man.

The Greeks tell us that many of their philosophers visited Egypt and Chaldea and learnt much from their priests. There is no reason to doubt this, but all the science that was brought back was the practical foundations of medicine, astronomy and mathematics, which were later transfigured by the Greek genius from the status of crafts to that of philosophies and sciences. The Egyptian mind was practical, ordered, religious, deeply reliant on tradition. The Greeks had that rarest quality

of being able to discard preconceived ideas, and from their knowledge of nature alone, defective as it was, to deduce a scientific system. Their sense of harmony, balance and proportion found its finest expression in Geometry, that most complete, harmonious and regular department of thought. The weakness of Greek science was its neglect of detail. Modern science measures the wings of thousands of flies and catalogues the markings of mice; from masses of insignificant facts it deduces general principles, such as the laws of inheritance, which are then rigorously checked by repeated experiments. The Greek philosopher commonly started from a very few facts which were common knowledge; from these he deduced a principle in terms of which he could explain the fundamental problems of man—life, death, the origin of the world and the nature of thought. For the Greek the fact of having found a consistent explanation was enough; no attempt was made to devise crucial experiments as a test of physical theories.

The Greek natural philosophers were interested in two chief matters:—

1. The nature of matter, spirit and motion.
2. The creation of the universe, its structure, and the nature and position of the sun, moon, planets and stars.

Thales was the first man whom we know to have conducted any rational and general inquiry into the nature of things. He was born about 640 B.C. at Miletus, one of the Ionian colonies. He is said to have travelled to Egypt and to have learnt there the elements of mathematics, such matters, we may suppose, as Ahmes set down a thousand years earlier. He was not satisfied to use

geometry as did his teachers; he *studied* it and, we learn, discovered three or four important theorems. But, most significant was his suggestion that the world had arisen, not by an external act of a god, but in the course of nature and from a single substance, which he believed to be water. Man has an innate tendency to believe that all things are derived from a single source; a conviction which, perhaps, arises from the perception that things visibly change into one another—iron into rust, food into flesh. Such changes can obviously be explained by the hypothesis that all substances are modifications of the same material. To-day we say that all things are made of electrons, protons and neutrons: whether these have any common "substance" we cannot say. The question would, to-day, hardly be asked, for, like Heraclitus, we conceive of the world as of the nature of action rather than substance. We must applaud the choice of Thales; for water, universally present, basis of life, agent of geological change, is of all visible substances the most nearly fundamental.

The philosophers who succeeded Thales agreed with him in looking for One principle from which All is derived. Anaximander (611–546 B.C.) took as his principle *That-which-is-unlimited,* a kind of primitive matter which generated inexhaustibly the materials of the world. Anaximenes (sixth century B.C.) believed that Air by condensation and rarefaction was modified to form all kinds of matter. These philosophers anticipated the viewpoint of the chemist: they were interested in the stuff of which the world was made. Heraclitus (510-450 B.C.) envisaged the universe in its dynamic aspect as changing, moving, growing, and decaying; to his mind the motive power of the world was the essential stuff of it. He selected the restless element of Fire as his first principle;

his fire was, of course, not a material flame, but a concept akin to the modern Energy. The Eleatic philosophers, with whose arguments it is difficult to be in sympathy to-day, saw the world as an immutable and motionless Being, and held that all change was but illusion. The conclusions of all these philosophers were, in themselves, of little value, but show us a picture of the first speculations about science in an age when such speculations were still new.

Pythagoras (570–500 B.C.) and his followers saw not a world of matter nor a world of energy, but a world of form. The Pythagorean ideas had no sounder experimental basis than had those of his forerunners and contemporaries; but form was a property which could be treated by arithmetic and geometry, the study of which was congenial to the Greeks. The Pythagorean view was therefore soon supported by ever-increasing discoveries of the wonderful regularities of the properties of numbers and geometrical figures, discoveries which confirmed the belief that these were the basis of the structure of the world. For the Pythagoreans, numbers were real essential things; there was a number of a man and a number of a horse, which made them man and horse respectively. They discovered that the pitch of the note emitted by the string of a musical instrument depended in a mathematically definable way upon the length of the string; thus they found that if the string of a musical instrument were doubled in length it would sound a note an octave lower than before, and so on: and this discovery, perhaps the first quantitative piece of scientific work, seemed to them to prove that numbers were connected with that noble organ of the soul which perceived harmony. The Pythagoreans developed a mystical and highly fanciful

philosophy, informed by a lofty spirit; their doctrines, like those of Democritus, Plato and Aristotle, exerted on the world's thought an influence which is still an unseen living force.

MEDICINE IN GREECE

Philosophy—in the sense of speculation about ultimate things—was by no means the sole scientific achievement of the Greeks; every department of Egyptian and Babylonian science was developed, improved and rationalised by them.

Under the Greeks medicine regained and surpassed the heights it had touched in the days of ancient Egypt when the Edwin Smith Surgical papyrus was written.

The greatest figure in ancient medicine is Hippocrates of Cos. Some seventy works are attributed to him, but when examined closely they are seen to be by different hands. Hippocrates was born in the island of Cos about 460 B.C. How far he was responsible for any of the seventy works of the Hippocratic collection is not known. Suffice it to say that in the fourth and fifth centuries B.C. these works were being written and for the first time in the world's history displayed not only a practical, but also a scientific or, at least, a philosophic view of medicine. The Hippocratic theory of medicine would not greatly commend itself to us to-day; for the Greeks, of course, were far from having even the remotest idea of the working of the body. It was believed that the body had four liquid constituents or humors, namely phlegm, blood, yellow bile, and black bile, and that a harmonious blending of these was a condition of health. In addition the four "powers" of heat, cold, moisture and dryness had to be

balanced. The notion that the healthy body was in a state of dynamic balance was sound; but the theory is wholly useless as a guide to diagnosis or treatment. But, as always in medicine, the men were better than the theories, and in the Hippocratic books we find beautifully clear and accurate descriptions of cases—models of clinical observation. Here is such a description:—

"In Thasos the wife of Delearces, who lay sick on the plain, was seized after a grief with an acute fever with shivering. From the beginning she would wrap herself up, and throughout, without speaking a word, she would fumble, pluck, scratch, pick hairs, weep and then laugh, but she did not sleep; though stimulated, the bowels passed nothing. She drank a little when the attendants suggested it. Urine thin and scanty; fever slight to the touch; coldness of the extremities.

"*Ninth day*. Much wandering followed by return of reason; silent.

"*Fourteenth day*. Respiration rare and large with long intervals, becoming afterwards short.

"*Seventeenth day*. Bowels under a stimulus passed disordered matters, then her very drink passed unchanged; nothing coagulated. The patient noticed nothing; the skin tense and dry.

"*Twentieth day*. Much rambling followed by recovery of reason; speechless; respiration short.

"*Twenty-first day*. Death.

"The respiration of this patient throughout was rare and large; took no notice of anything; she constantly wrapped herself up; either much rambling or silence throughout."[1]

[1] *Hippocrates*, Vol. I, p. 283. Translated by W. H. S. Jones. Loeb Library, Heinemann, London.

The medical treatment recommended by Hippocrates was sensible and conservative: good nursing, wholesome food and good air were more esteemed than drugs. The primitive belief that sickness was a supernatural visitation received the first open attack from the followers of Hippocrates, in the treatise where it is avowed that the "sacred disease" (epilepsy) is no more god-sent than any other. This passage is so typical of the spirit of Greek science and would have been so wholly impossible in any previous age that it is worth quoting *in extenso*:—

THE SACRED DISEASE

I. "I am about to discuss the disease called 'sacred.' It is not, in my opinion, any more divine or more sacred than other diseases, but has a natural cause, and its supposed divine origin is due to men's inexperience and to their wonder at its peculiar character. Now while men continue to believe in its divine origin because they are at a loss to understand it, they really disprove its divinity by the facile method of healing which they adopt, consisting as it does of purifications and incantations. But if it is to be considered divine just because it is wonderful, there will be not one sacred disease but many, for I will show that other diseases are no less wonderful and portentous, and yet nobody considers them sacred. For instance quotidian fevers, tertians and quartans,[1] seem to me to be no less sacred and god-sent than this disease, but nobody wonders at them. Then again one can see men who are mad and delirious from no obvious cause, and committing many

[1] Malarial fevers recurring at intervals of one, three or four days.

strange acts; while in their sleep, to my knowledge, men groan and shriek, others choke, others dart up and rush out of doors, being delirious until they wake, when they become as healthy and rational as they were before, though pale and weak; and this happens not once but many times. Many other instances, of various kinds, could be given, but time does not permit us to speak of each separately.

II. "My own view is that those who first attributed a sacred character to this malady were like the magicians, purifiers, charlatans and quacks of our own day, men who claim great piety and superior knowledge. Being at a loss, and having no treatment which would help, they concealed and sheltered themselves behind superstition, and called this illness sacred, in order that their utter ignorance might not be manifest. They added a plausible story, and established a method of treatment that secured their own position. They used purifications and incantations; they forbade the use of baths, and of many foods that are unsuitable for sick folk—of sea fishes: red mullet, black-tail, hammer and eel (these are the most harmful sorts); the flesh of goats, deer, pigs and dogs (meats that disturb most of the digestive organs); the cock, pigeon and bustard, with all birds that are considered substantial foods; mint, leek and onion among the vegetables, as their pungent character is not at all suited to sick folk; the wearing of black (black is the sign of death); not to lie on or wear goatskin, not to put foot on foot or hand on hand (all which conduct is inhibitive). These observances they impose because of the divine origin of the disease, claiming superior knowledge and alleging other causes, so that, should the patient recover, the reputation for cleverness

may be theirs; but should he die, they may have a sure fund of excuses, with the defence that they are not at all to blame, but the gods. Having given nothing to eat or drink, and not having steeped their patients in baths, no blame can be laid, they say, upon them. So I suppose that no Libyan dwelling in the interior can enjoy good health, since they lie on goat-skins and eat goats' flesh, possessing neither coverlet nor footgear that is not from the goat; in fact, they possess no cattle save goats and oxen. But if to eat and use these things engenders and increases the disease, while to refrain works a cure, then neither is godhead to blame nor are the purifications beneficial; it is the foods that cure or hurt, and the power of godhead disappears.

III. "Accordingly I hold that those who attempt in this manner to cure these diseases cannot consider them either sacred or divine; for when they are removed by such purifications and by such treatment as this, there is nothing to prevent the production of attacks in men by devices that are similar. If so, something human is to blame, and not godhead. He who by purifications and magic can take away such an affection can also by similar means bring it on, so that by this argument the action of godhead is disproved. By these sayings and devices they claim superior knowledge, and deceive men by prescribing for them purifications and cleansings, most of their talk turning on the intervention of gods and spirits. Yet in my opinion their discussions show, not piety, as they think, but impiety rather, implying that the gods do not exist, and what they call piety and the divine is, as I shall prove, impious and unholy.

IV. "For if they profess to know how to bring down

the moon, to eclipse the sun, to make storm and sunshine, rain and drought, the sea impassable and the earth barren, and all such wonders, whether it be by rites or by some cunning or practice that they can, according to the adepts, be effected in any case I am sure that they are impious, and cannot believe that the gods exist or have any strength, and that they would not refrain from the most extreme actions. Wherein surely they are terrible in the eyes of the gods. For if a man by magic and sacrifice will bring the moon down, eclipse the sun, and cause storm and sunshine, I shall not believe that any of these things is divine, but human, seeing that the power of godhead is overcome and enslaved by the cunning of men. But perhaps what they profess is not true, the fact being that men, in need of a livelihood, contrive and devise many fictions of all sorts, about this disease among other things, putting the blame, for each form of affection upon the particular god. If the patient imitate a goat, if he roar, or suffer convulsions in the right side, they say that the Mother of the Gods is to blame. If he utter a piercing and loud cry, they liken him to a horse and blame Poseidon. Should he pass some excrement, as often happens under the stress of the disease, the surname Enodia is applied. If it be more frequent and thinner, like that of birds, it is Apollo Nomius. If he foam at the mouth and kick, Ares has the blame. When at night occur fears and terrors, delirium, jumpings from the bed and rushing out of doors, they say that Hecate is attacking or that heroes are assaulting. In making use, too, of purifications and incantations they do what I think is a very unholy and irreligious thing. For the sufferers from the disease they purify with blood and such like, as though they were

polluted, blood-guilty, bewitched by men, or had committed some unholy act. All such they ought to have treated in the opposite way; they should have brought them to the sanctuaries, with sacrifices and prayers, in supplication to the gods. As it is, however, they do nothing of the kind, but merely purify them. Of the purifying objects some they hide in the earth, others they throw into the sea, others they carry away to the mountains, where nobody can touch them or tread on them. Yet, if a god is indeed the cause, they ought to have taken them to the sanctuaries and offered them to him. However, I hold that a man's body is not defiled by a god, the one being utterly corrupt, the other perfectly holy. Nay, even should it have been defiled or in any way injured through some different agency, a god is more likely to purify and sanctify it than he is to cause defilement. At least it is godhead that purifies, sanctifies and cleanses us from the greatest and most impious of our sins; and we ourselves fix boundaries to the sanctuaries and precincts of the gods, so that nobody may cross them unless he be pure; and when we enter we sprinkle ourselves, not as defiling ourselves thereby, but to wash any pollution we may have already contracted. Such is my opinion about purifications.

V. "But this disease in my opinion is no more divine than any other; it has the same nature as other diseases, and the cause that gives rise to individual diseases. It is also curable, no less than other illnesses, unless by long lapse of time it be so ingrained as to be more powerful than the remedies that are applied. Its origin, like that of other diseases, lies in heredity. For if a phlegmatic parent has a phlegmatic child, a bilious parent a bilious child, a consumptive parent a consump-

tive child, and a splenetic parent a splenetic child, there is nothing to prevent some of the children suffering from this disease when one or other of the parents suffered from it; for the seed comes from every part of the body, healthy seed from the healthy parts, diseased seed from the diseased parts. Another strong proof that this disease is no more divine than any other is that it affects the naturally phlegmatic, but does not attack the bilious. Yet if it were more divine than others, this disease ought to have attacked all equally, without making any difference between bilious and phlegmatic.

VI. "The fact is that the cause of this affection, as of the more serious diseases generally, is the brain."[1]

In these Hippocratic treatises surgery is shown to be at a high level. The treatment of wounds, fractures and dislocations is very soundly and clearly explained. Hippocrates treats medicine as a physical science, and though his theoretical knowledge is scanty, his face is set towards the modern scientific ideal. His sense of the loftiness of his calling must not go unmarked. The Oath of Hippocrates sets out almost completely the code of professional ethics which still adorns the medical profession.

We know, to-day, that the deduction from theoretical principles of the mode of action of a living body was a hopeless task. Long and patient observation, deductions and experiments have been needed to give the very imperfect understanding of living matter which we have acquired to-day. The Greeks had no liking for such work. Their intellects were, however, no less keen than

[1] *Hippocrates*, Vol. II, pp. 139–153, translated by W. H. S. Jones. Loeb Library. Heinemann, London.

those of any men who have lived, and it is in the realms of pure intellect—philosophy and geometry—that they succeeded.

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GREEK MATHEMATICS

Greek Mathematics was the science completely adapted to the Greek genius. Its concepts—points, lines, areas, etc.—could be exactly defined: a man and writing-materials was all that it demanded. Yet because it could be applied to real physical solids it seemed to provide a clue to Nature which could be worked out by pure intelligence. The progress of Geometry under the Greeks was rapid; we may summarise it by saying that in 650 B.C. the world's knowledge of geometry was contained in a few rule-of-thumb methods for measuring heights, areas, angles, etc.; by 550 B.C. in the hands of Pythagoras it was becoming a theoretical science, and by 450 B.C. his followers had discovered and proved about as much geometry as a matriculation candidate should know. About 300 B.C. Euclid wrote his *Elements*: such a beautiful, complete and logical exposition of geometry that, until some fifty years ago, a *literal* translation of it was the world's standard introductory textbook to Geometry. Archimedes, of whom more hereafter, used methods which had in them the germ of the calculus, and by 200 B.C. Greek Geometry had accomplished almost everything that pure geometry can do and a great deal that is now done by algebra and the calculus. This advance in Geometry was not significant for itself alone. Geometrical reasoning, in its certainty, lucidity and intellectual beauty afforded a model for all types of rational inquiry and a monument to the powers of human reason.

Greek arithmetic was much inferior to Greek Geometry because it lacked a satisfactory notation for expressing numbers. Much was discovered about factors and the properties of numbers, but ordinary computations remained cumbrous until the Hindu invention of the zero reached mediæval Europe.

GREEK ASTRONOMY

Astronomy made great progress among the Greeks. Not much is known about the actual observations made by them; the object of the philosophers was to discover what the heavenly bodies were and to find out and explain the laws which governed their movement. The development of Geometry made it possible for them to evolve a valuable working theory capable of interpreting these movements with fair accuracy.

The apparent movement of the stars, sun and moon can be directly observed. The actual movements can only be deduced if the object relative to which they are moving be specified. The two competing theories were the *geocentric,* in which the earth is supposed to be still and the other bodies move, and the *heliocentric,* in which the sun and stars are held to be motionless while the earth and other bodies move. Both theories were held by Greek philosophers; the geocentric theory, largely owing to the influence of Aristotle, gained the day. A perfectly consistent explanation of the heavenly motions can be and was constructed on this basis and was not superseded for nearly 2000 years.

The first representation of the universe was made by Anaximander, who supposed the earth was cake-shaped

and was surrounded by a sphere of air outside which there was a sphere of fire: the sun, moon, and stars were apertures in the wall of the sphere of fire; this sphere rotated, so giving rise to the appearance of movement. This simple system could not account for the motion of the planets, moon and stars, relative to each other and the Pythagoreans supposed the universe to consist of separate concentric spheres of crystal, which respectively carried along by their rotation the moon, the sun, each of the five planets and the whole body of fixed stars (*cf.* Fig. 13). They believed that these spheres in their rapid motion emitted a music to be perceived only by those of the most exalted faculties. Anaxagoras (*c.* 500–428 B.C.) put forward the belief that the sun was a mass of blazing metal as big as Greece and the heavenly bodies in general masses of rock, but this view did not meet with approval. The Pythagorean system of concentric spheres was modified and mathematically treated by great geniuses such as Eudoxus and finally served as a very adequate explanation of the movements of planets and stars. The final statement of the theory was made by Ptolemy (p. 47) in Alexandria.

PLATO AND ARISTOTLE

The greatest of Greek philosophers were Plato and Aristotle. Their thought profoundly influenced the whole of the workings of the human mind and is powerful even to-day. Plato's genius is imbued with the mysticism we have noted in the work of Pythagoras; he is not greatly interested in the detail of Natural Science. The soul to him is all-important; the bodies it inhabits in successive transmigrations are mere prisons. Aristotle, on the other

hand, is the more complete philosopher, interested as he was in every department of knowledge.

Plato lays the stress on the Universals; to him the real thing about individual horses was the Idea of Horse of which they were copies. To Aristotle the individual horses of the world were real: the notion of Horse did not have a real existence apart from these individual horses. Aristotle, therefore, gave more importance to the individual material things in the world and less to the ideas in the mind of man: he was, therefore, much nearer to the modern man of science than was Plato.

Plato set out his theory of the nature of the world in the *Timaeus*. He looked on the world in a manner which was wholly sundered from the modern point of view. The universe was, to him, only a likeness of an unchanging eternal model, not to be apprehended by human senses; consequently no account of it could be more than a "likely story."

The universe he believed to be living, a blessed god, animated by a universal soul, which was the primary cause of motion. It was closed, limited and spherical. Its parts were all constructed according to mathematical and harmonic ratios. The primary elements were earth, air, fire and water, present in mathematical ratios and composed of parts having fixed geometrical forms. Plato's general scheme evidently derived rather nearly from that of the Pythagoreans. The Natural Science displayed in the *Timaeus* cannot be rated very highly; the whole work is composed of a minimum of ascertained fact explained by very complex mathematical and musical principles. These explanations are based throughout on the operation of a divine Reason; consequently the harmony or fittingness of a phenomenon was, for Plato, a good reason to believe

in its existence. The Platonic outlook was, then, almost contrary to the modern conception of Natural Science, which tends ever more to eliminate conscious guidance from its world.

Aristotle (384–322 B.C.) was born in the coast town of Stagira. He studied for twenty years under Plato, was tutor to Alexander the Great, and carried on a school of philosophy in Athens. His achievements were enormous. He founded Logic, the science of distinguishing correct arguments from incorrect, and Ethics, the science of human conduct.

Aristotle divided the world into three classes, Nature, God and Man. He believed that every substance whatever was a compound of essence and matter. The essence was what gave the thing its individuality: thus all horses partook of the essence *Horse*. His theory concerning the ordinary matter of which earthly bodies are composed, was that it consisted of a *prime matter* which had no other property save that of being material. This prime matter never existed in this unmodified state. It served as a basis for the four "elements", earth, water, air and fire, by which were meant, not material substances, but qualities something like the modern notions of solidity, liquidity, volatility, and energy. The prime matter was potentially any kind of material, the particular proportion in which the elements were present made it a particular kind of material.

God he regarded as an essence wholly good and not at all conjoined with matter; God was the first cause of all things and source of the motion of the universe. Man and animals had, as essence, a soul, but man alone had a rational spirit; unlike the other animals he had an intellect which had no organ for its expression and was divine. Man was natural in bodily matter, divine in intellect.

The interest of Aristotle in matter and in animals predisposes him to Natural Science, and he may be called the first biologist. His scientific works deal with the explanation of many phenomena observed in everyday life, but especially treat of Natural History—the habits, structures, and development, of animals and plants. Much he observed for himself, a procedure by no means Greek. Sea-beasts he knew well; brought up on the shores of the Ægean, he had watched the rock-pools and the fishermen's catches. He had noticed birds and small beasts, and insects; his personal observations are accurate, detailed and pertinent. The stories he relates of elephants, lions and camels are less accurate, but even in his attitude to travellers' tales he showed a wise scepticism.

Aristotle had an ordered and logical mind and was the founder of classification. His doctrine of essences (p. 37) made the notion of species important to him and he therefore sought to classify the many living species he knew. He conceived of a *ladder of nature* rising from the inorganic through the groups of plants, sponges, ascidians, etc., shelled molluscs, insects, crustaceans, cephalopods, fishes, serpents, amphibians and lizards, birds, viviparous quadrupeds, cetaceans to man.

Considering that he was the pioneer of such a classification, his groupings were very sound, being based on a wide view of the species studied, and not on a few superficial characters. The weakest part of his classification was his division of the invertebrates, for without the microscope it was impossible to study the structure of most of the smaller animals.

Aristotle was extremely interested in the reproduction of animals. He believed, naturally though incorrectly, in the spontaneous generation of the lower animals. He

reached the conception that in the higher animals the female contributes something in the nature of an "egg", and the male a "sperm". The sperm he believed had a *power* by which the egg was caused to develop and fashioned into the animal, but he did not consider that there was any fusion of material from the male and female; here some of the later Greek philosophers were at issue with him.

Aristotle's works on the other branches of science were less successful. Many of his ideas in physics were little more than opinions; but, being accepted by the world, and in the Middle Ages made almost articles of faith, became serious obstructions to science. Thus Aristotle believed that motion could only be maintained by continual application of a force; that a vacuum was impossible; that certain things were light by nature and tended to rise spontaneously, while others were heavy and tended to fall. Such conceptions as these were shown to be false only at the cost of much bitter controversy, and as late as the seventeenth century.

The influence of Aristotle was incalculable. To the learned of the first fifteen centuries of the Christian era he was "The Philosopher," and for almost two thousand years his works remained one of the few standard authorities on science and his assertion of a scientific fact was considered to be the best proof of its truth. In the thirteenth century his philosophy was adopted as the official view of the Catholic Church, and it was not until the end of the sixteenth century that science outgrew his teachings.

After the death of Aristotle, Theophrastus, the first great botanist, became head of his school of philosophy. He described in some detail and with very fair accuracy

a large number of plants and had some idea of the nature and purpose of their more obvious organs. His work remained the best botanical text-book until the Renaissance.

GREEK LEARNING AT ALEXANDRIA

While Aristotle was yet alive, Alexander the Great conquered the Eastern world and founded cities whose inhabitants spoke Greek and had the Greek habit of thought. In 332 B.C. Alexandria was founded, and it remained for years the centre of the world's culture. The city was laid out in very modern fashion as a gridiron of parallel streets, beneath each of which was a subterranean canal. Two main streets, two hundred feet wide, met at the centre of the city. On the island of Pharos, connected by a mole to the mainland, stood the Great Lighthouse, said to have been 400 feet high, surmounted by a beacon whose light is believed to have been focussed into a beam by some contrivance of mirrors. The city flourished exceedingly and was a centre of wealth and learning. Alexander's successor, Ptolemy Soter, who reigned over Egypt from 323 to 285 B.C., was a patron of learning. He founded a great library and concentrated in it the whole knowledge of the ancient world. He built an Academy of Science, which was almost a modern University. Ptolemy Soter's successors were likewise patrons of learning and Alexandria remained the world's brain-centre from 300 B.C. to about A.D. 300, after which time, in consequence of the break-up of the Roman Empire, the commerce which was its life-blood began to wane. In A.D. 616 it was taken by Chosroes, the king of Persia,

and in A.D. 640 it was again taken and destroyed by the Arabians.

Greek culture in Alexandria was grafted on a different stock from that on which it had grown. As might be expected in a city which was a great port and market and which stood between Europe and the East, the population was exceedingly mixed. It was almost equally Greek, Jewish and Egyptian. The Greek scientific genius, the Jewish monotheistic religion, and the mysticism from Egypt and the East all became blended. The passion of the learned for science and philosophy, intense as it was in the second and third centuries B.C., gave place in the first centuries of the Christian era to a more intense religious fervour. The great intelligences of the Greek world up to A.D. 100 tended to the study of philosophy and science, but after this time we find an increasing tendency towards syntheses of science and religion, such as the neo-Platonic systems; finally after about A.D. 400 the world's intellectual interests are almost entirely directed to Christian theology.

Our concern, then, will mainly be with the earlier part of the Alexandrian culture. Even here we notice a marked difference from the science of Greece. Alexandrian science, as befitted that which had grown up in a vast commercial centre, was much more practical and less philosophic than that which had grown out of the simpler city-states of Greece.

As Alexandrian science declines we find an exaggerated respect for the ancient authors. Men of science no longer write their own books: they write commentaries upon Aristotle's works, containing in footnotes, so to speak, their own additions to science. This intense respect for antiquity persisted in Byzantium, in Islam and in Western

Europe, and was not effectively broken until the seventeenth century.

ROMAN SCIENCE

Throughout the three hundred years of Alexandrian brilliance, the Roman power had been steadily rising and in the first and second centuries A.D., Rome, the mistress of the world, attracted to herself most of the world's literary and poetic talent. But the Roman, man of affairs, soldier and lawgiver, had little taste for pure inquiry and the only considerable monuments of his scientific achievements are the great poem of Lucretius *On the Nature of Things*, the *Quæstiones Naturales* of Seneca and the *Natural History* of Pliny. The theme of the poem of Lucretius is derived from the Greek philosophers Epicurus and Democritus, and, though later in time than the works of the Alexandrian men of science, it may engage our attention first. Aristotle's "four-element" theory of matter (p. 37) was destined to remain the standard explanation until the seventeenth century. Democritus of Abdera (*c.* 470–380 B.C.), who lived rather earlier than Aristotle, had set out a totally different theory, namely, that the world consisted of atoms—tiny, unalterable, indivisible material particles, ever moving in empty space. Democritus held that the differences between the various kinds of matter were due to differences in the size and shape of their atoms, and in the kind and the proportions of these atoms. Democritus was right, but his atomic theory was but a barren truth because he had neither the means to prove it, nor the equipment to deduce and follow up its consequences. The ideas of Democritus, as modified by Epicurus, furnished the

scientific notions which were the foundation of the work of Lucretius.

Lucretius, one of the world's great poets, was born in 94 B.C. and died in 55 B.C. Towards the end of his life he completed his noble epic *De Natura Rerum, On the Nature of Things.* To us it seems curiously modern. Lucretius bases his explanations of nature on the atom: he attacks with fierce contempt the notions of religion: he denies the immortality of the soul: these views he derived, with much modification, from the philosopher Epicurus. Lucretius rejects the idea of the creation of the world by a god. He sees a primal universe containing an infinite number of atoms falling by their own weight through infinite space. They swerve, then meet and clash; thus the atoms first build up small particles, these coalesce to large masses, and finally to worlds. The chance interaction of atoms, he believed, built up living creatures: the soul was an aggregation of atoms, material, but more subtle than those of the body. The poem, great scientific achievement as it is, strikes us rather as a nobly-conceived attempt to free man's soul by destroying the illusion of the gods, than as a scientific description of the universe; for, indeed, almost all the Lucretian explanations of phenomena in terms of atoms are illogical as well as untrue.

After Lucretius, no important generalisations about the composition of matter were made until Boyle published the *Sceptical Chymist* in 1661. The Aristotelian theories held the day, though in place of or in addition to their "elements" of earth, air, water and fire, other principles, such as "mercury" and "sulphur" were added by the Arab chemists: to these Paracelsus added "salt".

The work entitled *Quæstiones Naturales,* written by the

statesman, tragedian and moral philosopher, Seneca, about A.D. 64, deals largely with meteorology and physical geography. The work is of no great merit: the author is first a moralist, then a man of science, and is chiefly concerned with the moral aspect of the universe.

The last great scientific work of Rome, the *Natural History* of Pliny, is a most curious collection. Pliny the Elder was a state official, a man of affairs, and by no means a man of science. He set himself to amass all the available knowledge bearing on Natural Science. He wrote on astronomy, medicine, zoology, geology, geography, technology of all kinds. He collected information from earlier writers, Greek and Latin, from technical men and from travellers' tales. The result is a hotch-potch of valuable information and absurd fables without much arrangement or order. None the less it tells us something of the folk-medicine which preceded scientific medicine; moreover, it is the source of most of our available information about the arts and crafts of the Romans of the first century A.D.

MEDICINE IN THE ALEXANDRIAN PERIOD

Medicine reached no very high level in Rome, but in Alexandria and later under Galenus of Pergamum great advances were made.

The Roman author and physician, Cornelius Celsus, flourished probably in the early part of the first century A.D. His system is based on Hippocrates and on the work of later physicians, surgeons and anatomists whose books are lost. It seems unlikely that he added anything himself to medical science. Celsus advocated the necessity of learning anatomy by observation of the patient and

dissection of the human dead, but regarded as cruel and needless the vivisection of men which, he said, had been practised on condemned criminals by Herophilus and Erasistratus.

Far more famous than Celsus was Galenus (*c.* A.D. 130–200) known to us as Galen. His works present to us the harvest of the ancient medical knowledge and were the standard text-books of medicine for 1500 years; in fact, even up to the middle of the eighteenth century, Galen's authority carried considerable weight. It is always difficult to tell how much a classical author discovered or recorded for himself, and how much he borrowed from earlier authors without acknowledgment. For this reason it is difficult to assess the work of Galen. He certainly used the results of two great anatomists, Erasistratus and Herophilus, who lived about 300 B.C.; his own knowledge of anatomy was largely, but by no means wholly, gained from the pig and the ape, for the dissection of human bodies was in his time, as in many others, considered to be an impious act. The anatomy, pig-anatomy as it was, recorded in his works was wonderfully accurate, and was but little improved on until the sixteenth century.

Galen had a clearer idea of the motion of the blood than had earlier authors. The arteries of a dead man are found to be empty, and they were consequently believed to be air-tubes, a view which, despite Galen's work, persisted throughout the Middle Ages. Galen, by laying bare a living artery, tying it in two places and then opening the intervening part, showed it to be full of blood. He realised that the arteries were connected to the veins, but does not seem to have understood the action of the heart. Galen realised the importance of anatomy to

surgery in enabling the surgeon to avoid nerves, arteries and veins. He made a most lengthy study of the pulse. Galen went far towards understanding the more obvious structures and functions of the brain. He makes perhaps the earliest declaration of the attitude of science to evidence, for, says he, ". . . although I confess the fault, and may be reprehended for it, for throughout my life I have adhered to it, I never confided in what others said, unless I was satisfied of the same by my own experience, so far as it was in my power." His words are justified by his experimental work upon animals and in his attitude to the assertions of earlier authors. Therein lies the secret of his scientific eminence.

The weakest part of all ancient medicine was its pharmacology; this is not surprising, for the assessment of the value of drugs is even to-day exceedingly difficult. Many medicaments extolled twenty years ago are now thought useless; we must not be too surprised, then, that Galen, in addition to many valuable drugs, some of which originated with the Greek physicians, used remedies disgusting to us, such as snails, worms, bugs, the ear-wax and excrement of dogs. The tendency to prepare cure-all medicines with sixty or eighty ingredients is notable; such medicines persisted till the eighteenth century. Galen was an advocate of blood-letting, and is in a measure responsible for the heavy death-roll which resulted from the abuse of this practice in the following seventeen centuries.

LATER GREEK ASTRONOMY AND GEOGRAPHY

There was a period in Greek astronomy when the theory that the earth was the centre of the system of sun,

planets and stars was opposed by the modern notion that the sun is the centre round which earth and planets alike rotate. Heraclides of Pontus (*c.* 388–315 B.C.) put forward the theory that the earth rotated on its axis and Aristarchus of Samos, who lived about 310–230 B.C. developed this. Archimedes (p. 53) says of Aristarchus:

> "His hypotheses are that the fixed stars and the sun remain unmoved, that the earth revolves about the sun in the circumference of a circle, the sun lying in the middle of the orbit, and that the sphere of the fixed stars, situated about the same centre as the sun, is so great that the circle in which he supposes the earth to revolve bears such a proportion to the distance of the fixed stars as the centre of the sphere bears to its surface."[1]

Here is the essence of the Copernican theory.

Why was this theory rejected and the geocentric view preferred? The reason perhaps was that the orbit of the earth is not in fact a circle, but an ellipse; and that therefore, as Tycho Brahe and Kepler later found, the theory in its simplest form is not adequate to explain the planetary motions. Ptolemy's theory of excentrically rotating spheres with other spheres bearing the heavenly bodies rolling between them (like ball-bearings) did in fact explain the actual observations very well and was justly preferred. It is unfortunate that the notion of elliptical orbits did not occur to the Greeks, for they were quite capable of building up the appropriate mathematical theory.

The Alexandrian Period saw the summing-up and

[1] *The Copernicus of Antiquity*. Heath. S.P.C.K., 1929.

perfection of the ancient astronomy. The men responsible for this great task were Eudoxus of Cnidos who lived about 370 B.C., Hipparchus (*c.* 130 B.C.), and the mathematician, geographer, and astronomer Claudius Ptolemaeus, usually known as Ptolemy, who flourished about A.D. 130–140. It is difficult to know how much we should ascribe to each of these authors, since the works of Hipparchus are lost. Ptolemy collected and studied the ancient observations and himself made others; from these he worked out a system which, though complicated, gave a very complete explanation of the movements, risings, settings, etc., of the heavenly bodies. Ptolemy's great work, the *Syntaxis Mathematica,* was later named by the Arabs the *Almagest* (Greatest of Books). The first part contains a general outline of astronomy. The earth he supposed to be spherical and at the centre of the universe: the heavens

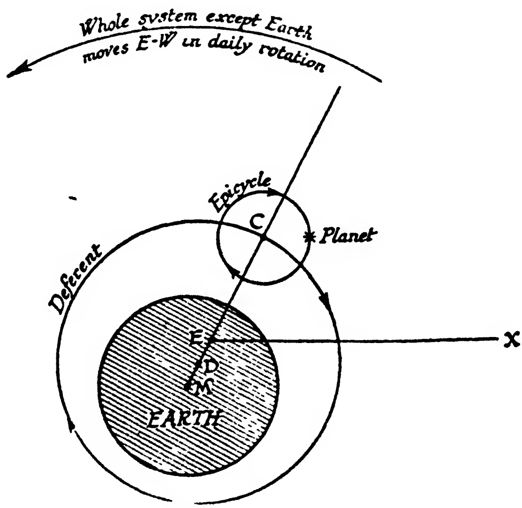


FIG. 4
The orbit of the Planet Saturn according to the Ptolemaic Theory.

·e spherically round it. The earth is very small, a mere point in fact, in relation to the universe. The motions of the planets he explained by a combination of circular motions; this is clearly necessary in any system where the earth is supposed to be still, for each planet must have its own circular motion relative to the sun while the whole universe has a circular motion relative to the earth.

In Fig. 4 is represented the Ptolemaic explanation of the motion of a planet. The earth remains motionless at the centre. The planet is carried on a sphere which rotates, and so revolves in a circular orbit—the epicycle. The centre of the epicycle is carried on another rotating sphere and so describes another circle (the deferent) round the earth. The centre of the deferent (D) is not at the centre of the earth (L). The centre of the epicycle does not move uniformly round the deferent but in such a manner that the angle between it and a point called the equant and some other fixed point increases uniformly. This accounted for the motions of the planets relative to the stars. The daily motion of the heavens was accounted for by supposing the whole system of spheres to rotate from East to West in a 24-hour period. This system with its vast material spheres rotating with gigantic velocities seems absurdly improbable, but it is doubtful whether Ptolemy regarded these spheres as more than a mathematical convention. The system was amenable to mathematical treatment and enabled the positions of the heavenly bodies to be predicted with fair accuracy.

To work out an astronomy on this basis it was necessary to have a very good knowledge of the geometry of the circle and of spherical trigonometry (the geometrical study of triangles drawn on a sphere). Ptolemy's *Almagest*

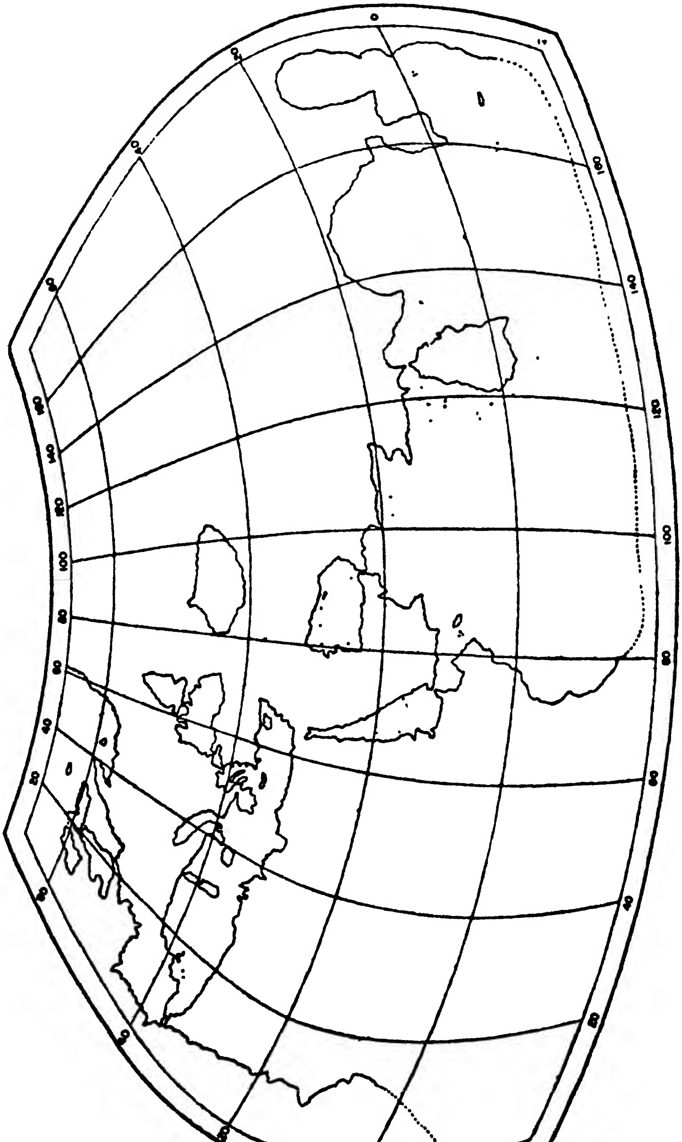


Fig. 5

THE WORLD ACCORDING TO PTOLEMY

deals in detail with the length of the day and year, the precession of the equinoxes, eclipses, the motions of the stars and planets. It also treats of methods of observation of the position of the stars, and catalogues some 1022 of these. The *Almagest* was the peak of astronomical exposition, and for 1400 years remained substantially unchallenged.

Ptolemy was also a great geographer. The earliest idea of the Greek was that the world was a flat disc surrounded by an ocean-river. The Pythagoreans regarded the world as a sphere—for only the perfect figure could be suitable for the god-world. Aristotle brought his scientific mind to bear on geography and gave good reasons for the sphericity of the earth. He suggested the existence of frigid polar zones, a torrid equatorial zone, and two intermediate temperate zones. Eratosthenes, about 250 B.C., measured by sound astronomical methods the circumference of the globe, and it became clear that the inhabited world known to the ancients was but a small part of its surface. There arose a general belief in distant inhabited lands, as yet unknown. Descriptive geography received some attention. Several authors wrote descriptions of foreign lands. Notable among these is Strabo (*c.* 63 B.C.–A.D. 24) who wrote a descriptive geography, which was partly based on his own personal travels.

Many of the early travellers brought back strange tales of strange races of men, of

> . . . Anthropophagi, and men whose heads
> Do grow beneath their shoulders. . . .

Their stories were handed on and believed for the best part of two thousand years. Fig. 6 is a sixteenth-century wood-cut of some of these ancient misunderstandings.

FIG. 6
Sixteenth-century woodcut of strange races of men derived from ancient travellers' tales.

Eratosthenes arrived at the very accurate figure of 25,000 miles for the circumference of the earth. Unfortunately Ptolemy relied on other observations and took the much less accurate value of 18,000 miles. Ptolemy used in his writings all the knowledge of previous writers. Not only did he treat of geography in its mathematical aspect, but he also undertook the enormous labour of constructing as accurate a map of the known world as was then possible. He collected all the known observations of latitude and longitude and the most reliable estimates of distance. There was, of course, no hope of making a correct map of the known world without taking observations of latitude and longitude in every known district. This task was made impossible by the absence of organisation and the difficulties of transport. Consequently Ptolemy was able to make a map of the world which was fairly correct in its delineation of the Mediterranean

region but increasingly incorrect in its picture of more distant lands. No actual map has survived from this period, but by plotting Ptolemy's records of latitude and longitude, his map can be reconstructed and is shown in outline in Fig. 5 Ptolemy was an astronomer and mathematical geographer: his physical and descriptive geography is inaccurate and scrappy.

Judged by our standards, Ptolemy's map is a poor one: yet it is a gigantic advance on anything which had been done before him.

ALEXANDRIAN MATHEMATICS AND PHYSICS

The mathematics of Euclid, Archimedes, Apollonius of Perga and others attained nearly to the limit of what can be accomplished in pure geometry. Arithmetic and algebra progressed but slowly, for there was as yet no simple notation for numbers and unknown quantities.

Mathematics is not a science, but a way of thinking logically. It is interesting at this time to see the Greek mind, to which reasoning came so easily, but to which experimental science was repugnant, proceeding from pure mathematics to its application, and thereby laying the foundation of physics and engineering.

Archimedes of Syracuse (287–212 B.C.) was the son of an astronomer. He was perhaps the greatest mathematical genius who has ever lived. He was utterly preoccupied with mathematical studies. In pure geometry he produced elegant and rigid proofs of theorems on spirals, conoids, spheroids, centres of gravity, etc., which at first sight would be thought impossible without the modern equipment of analytical geometry and the

calculus. In arithmetic he worked out a system allied to our modern use of indices for expressing any number, however great.

Archimedes was the first to work out the principle of the lever and balance in mathematical terms and to give a rigid treatment of centre of gravity. He may have had predecessors in statics, but the science of hydrostatics seems to be entirely his own invention. He originated the idea of specific gravity and gave a superb geometrical treatment of the positions taken by various floating solids.

The famous principle of Archimedes, which states that, if a solid be weighed in a fluid, it will be lighter than its true weight by the weight of the fluid displaced, has ensured that his name is known to every schoolboy. The story of the crown made for Hiero, King of Syracuse, is in all probability true. The tale exists in more than one version. Hiero suspected that the metal of his crown was not pure gold but was mixed with silver, and set Archimedes the problem of finding out what proportion of this metal was contained in the crown. Archimedes noticed that when he got into a perfectly full bath the volume of water which overflowed was equal to that of his own body. This gave him the solution and he is said to have run naked home from the baths shouting "*Eureka, eureka*"—"I have found it, I have found it." He solved the problem, probably, by finding the volume of water displaced by the crown and also by the same weight of gold and of silver respectively. If the volumes of water displaced by the crown, by its own weight of gold and by its own weight of silver respectively, are V, V_1, V_2, then the proportion of gold to silver by weight is $\frac{V_2 - V}{V - V_1}$.

Archimedes certainly invented a great number of

mechanical contrivances, but he thought these unworthy of a philosopher and did not write a book on them. Indeed the mechanical inventions of Archimedes, though remarkable for their period, are insignificant beside his mathematical achievement.

His inventive genius was displayed during the siege of Syracuse by the Roman General Marcellus. The story is told by Plutarch.

> "Hereupon Marcellus marched with his whole army, and encamped before Syracuse. . . . He made his attacks both by sea and land, Appius Claudius commanding the land forces, and himself the fleet, which consisted of sixty galleys, of five banks of oars, full of all sorts of arms and missive weapons. Besides these, he had a prodigious machine, carried upon eight galleys fastened together, with which he approached the walls, relying upon the number of his batteries, and other instruments of war, as well as on his own great character. But Archimedes despised all this; and confided in the superiority of his engines: though he did not think the inventing of them an object worthy of his serious studies, but only reckoned them among the amusements of geometry. Nor had he gone so far, but at the pressing instances of king Hiero, who entreated him to turn his art from abstracted notions to matters of sense, and to make his reasonings more intelligible to the generality of mankind, applying them to the uses of common life.
>
> "The first that turned their thoughts to *mechanics,* a branch of knowledge which came afterwards to be so much admired, were Eudoxus and Archytas, who thus gave a variety and an agreeable turn to geometry, and

confirmed certain problems by sensible experiments and the use of instruments, which could not be demonstrated in the way of theorem. That problem, for example, of two mean proportional lines, which cannot be found out geometrically, and yet are so necessary for the solution of other questions, they solved mechanically, by the assistance of certain instruments called *mesolabes,* taken from conic sections. But when Plato inveighed against them, with great indignation, as corrupting and debasing the excellence of geometry, by making her descend from incorporeal and intellectual to corporeal and sensible things, and obliging her to make use of matter, which requires much manual labour, and is the object of servile trades; then *mechanics* were separated from geometry, and being a long time despised by the philosopher, were considered as a branch of the military art. . . .

"When the Romans attacked them both by sea and land, they were struck dumb with terror, imagining they could not possibly resist such numerous forces and so furious an assault. But Archimedes soon began to play his engines, and they shot against the land forces all sorts of missive weapons and stones of an enormous size, with so incredible a noise and rapidity that nothing could stand before them; they overturned and crushed whatever came in their way, and spread terrible disorder throughout the ranks. On the side towards the sea were erected vast machines, putting forth on a sudden, over the walls, huge beams with the necessary tackle, which striking with a prodigious force on the enemy's galleys, sunk them at once; while other ships, hoisted up at the prows by iron grapples or hooks, like the beaks of cranes, and set on end on the stern, were

plunged to the bottom of the sea: and others again, by ropes and grapples, were drawn towards the shore, and after being whirled about, and dashed against the rocks that projected below the walls, were broken to pieces, and the crews perished. Very often a ship lifted high above the sea, suspended and twirling in the air, presented a most dreadful spectacle. There it swung till the men were thrown out by the violence of the motion, and then it split against the walls, or sunk, on the engine's letting go its hold. As for the machine which Marcellus brought forward upon eight galleys, and which was called *sambuca,* on account of its likeness to the musical instrument of that name, whilst it was at a considerable distance from the walls, Archimedes discharged a stone of ten talents weight, and after that a second and a third, all which striking upon it with an amazing noise and force, shattered and totally disjointed it.

". . . At last the Romans were so terrified, that if they saw but a rope or a stick put over the walls, they cried out that Archimedes was levelling some machine at them, and turned their backs and fled. Marcellus seeing this, gave up all thoughts of proceeding by assault, and leaving the matter to time, turned the siege into a blockade.

"Yet Archimedes had such a depth of understanding, such a dignity of sentiment, and so copious a fund of mathematical knowledge, that, though in the invention of these machines he gained the reputation of a man endowed with divine rather than human knowledge, yet he did not vouchsafe to leave any account of them in writing. For he considered all attention to *mechanics,* and every art that ministers to common uses, as mean

and sordid, and placed his whole delight in those intellectual speculations, which, without any relation to the necessities of life, have an intrinsic excellence arising from truth and demonstration only. Indeed, if mechanical knowledge is valuable for the curious frame and amazing power of those machines which it produces, the other infinitely excels on account of its invincible force and conviction. And certainly it is, that abstruse and profound questions in geometry, are nowhere solved by a more simple process and upon clearer principles, than in the writings of Archimedes. Some ascribe this to the acuteness of his genius, and others to his indefatigable industry, by which he made things that cost a great deal of pains appear unlaboured and easy. In fact, it is almost impossible for a man of himself to find out the demonstration of his propositions, but as soon as he had learned it from him, he will think he could have done it without assistance: such a ready and easy way does he lead us to what he wants to prove. We are not, therefore, to reject as incredible, what is related of him, that being perpetually charmed by a domestic syren, that is, his geometry, he neglected his meat and drink, and took no care of his person; that he was often carried by force to the baths, and when there, he would make mathematical figures in the ashes, and with his finger draw lines upon his body, when it was anointed; so much was he transported with intellectual delight, such an enthusiast in science. And though he was the author of many curious and excellent discoveries, yet he is said to have desired his friends only to place on his tombstone a cylinder containing a sphere, and to set down the proportion which the containing solid bears to the contained. Such was

Archimedes, who exerted all his skill to defend himself and the town against the Romans. . . .

"But what most of all afflicted Marcellus, was the unhappy fate of Archimedes; who was at that time in his study, engaged in some mathematical researches; and his mind, as well as his eye, was so intent upon his diagram, that he neither heard the tumultuous noise of the Romans, nor perceived that the city was taken. A soldier suddenly entered his room, and ordered him to follow him to Marcellus; and Archimedes refusing to do it, till he had finished his problem, and brought his demonstration to bear, the soldier, in a passion, drew his sword and killed him. Others say, the soldier came up to him at first with a drawn sword to kill him, and Archimedes perceiving him, begged he would hold his hand a moment, that he might not leave his theorem imperfect; but the soldier, neither regarding him nor his theorem, laid him dead at his feet. . . ."

Heron of Alexandria probably lived in the second century A.D. He wrote a most interesting work on mechanical contrivances, for the most part worked by the flow of water or the expansion of air. This work does not seem to describe his own inventions, and it probably derives from Ctesibius, who may have lived at about the same period as Archimedes. Almost alone among the ancients, Heron is less interested in theory than in practice. He seems to have been a practical surveyor, and wrote a treatise on this subject. His machines are not very complicated, but they are the first machines, other than the crane, the windlass and the waterwheel, that we hear of in history.

Most of his inventions seem strange to us, for they were

not directed to practical ends, but for the furtherance of religious shows or merely for conjuring tricks. Thus a fire lighted on an altar caused air in a tank beneath it to expand and to drive out water, the weight or pressure of which worked automata, opened gates, caused fountains to flow, etc. Water poured into a vase drove out air through the figure of a bird, which was thus caused to sing. A "penny-in-the-slot" machine (Fig. 7) for providing holy-water is mentioned; fire-engines, and organs whose blast was provided by hydraulic means are also described.

Heron's steam-engine, a simple reaction turbine, is shown in Fig. 8. The world-shaking invention of the

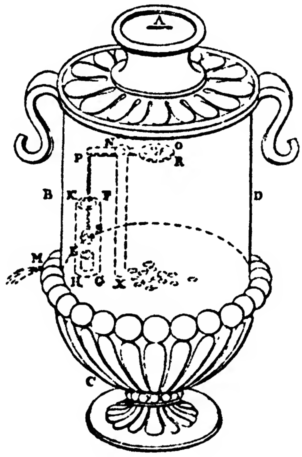


FIG. 7

"Penny-in-the-Slot" machine for delivering holy water, as described by Heron. The coin dropped in at A, depresses the plate R, so raising the stopper S. The coin then falls off the plate and the stopper again closes the exit-pipe. (From *The Pneumatics of Hero of Alexandria*. Ed. B. Woodcroft. London. 1851.)

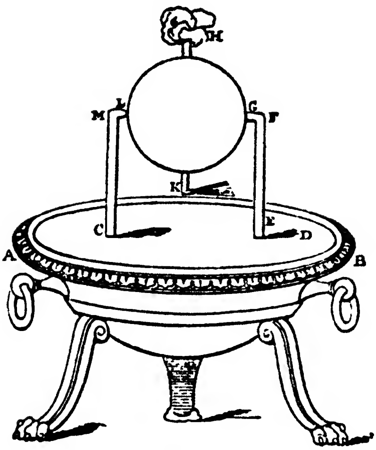


FIG 8
Heron's steam-turbine.
(From the same work as
Fig. 7)

steam-engine appears here in the guise of a toy. Here is the description of it.[1]

"Place a cauldron over a fire: a ball shall revolve on a pivot. A fire is lighted under a cauldron, AB, containing water, and covered at the mouth by the lid CD: with this the bent tube EFG communicates, the extremity of the tube being fitted into a hollow ball HK. Opposite to the extremity G place a pivot, LM, resting on the lid DC: and let the ball contain two bent pipes, communicating with it at the opposite extremities of a diameter, and bent in opposite directions, the bends being at right angles and across the lines FG, LM. As the cauldron gets hot it will be found that the steam, entering the ball through EFG, passes out through the bent tubes towards the lid, and causes the ball to revolve, as in the case of the dancing figures."

[1] *The Pneumatics of Hero of Alexandria.* Woodcroft, London, 1851.

A world of slave-labour did not need the power of steam, and for sixteen hundred years the idea lay dormant.

THE ORIGIN OF CHEMISTRY

The Greeks of the classical period felt no need for a science of Chemistry. Chemical principles had been used for thousands of years in the making of metals, glass, drugs, leather, dyes and the like, but no attempt was made to study materials under laboratory conditions before the first or second century A.D., at which period certain authors, of whom we know nothing but their names, wrote on Alchemy, that strangest of sciences, ostensibly concerned with the changing of base metal into gold. The origin of this notion is often thought to have arisen from attempts to make yellow alloys, debased gold and silver and various imitations of the precious metals: papyri describing such practical procedures have come down to us. The transmutation of metals into gold was quite consistent with the philosophy of the time, for a single prime matter was thought to be the basis of all things. Some of the early alchemists used fairly practical metallurgical processes which ought to have yielded passable imitations of the precious metals. But the most interesting to us are the alchemists who invented much of our modern laboratory technique: the earliest of these was Maria the Jewess, who may have lived in the second century A.D., and whose works exist only in fragments quoted by later authors. Her methods do not seem in the least adapted to accomplish their purpose, the making of gold, but their really interesting feature is that they describe well-designed laboratory apparatus for heating, fusion, filtration,

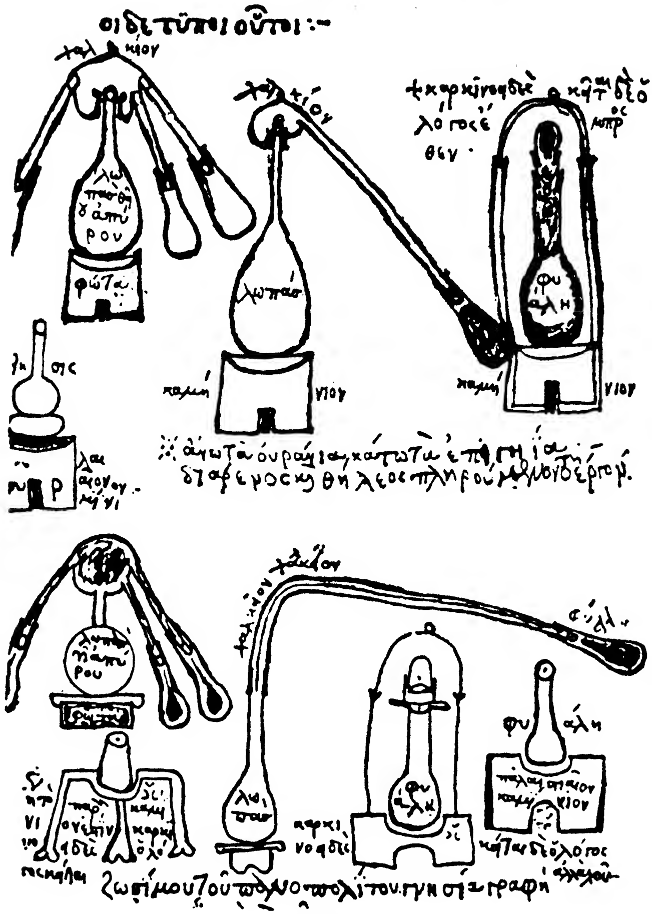


FIG. 9

· Drawings of Chemical apparatus dating from A.D. 200–500.

distillation, and sublimation. Apart from the invention of these fundamental pieces of apparatus, the Greek alchemists record very few chemical discoveries, for their aim seems to have been centred only on one practical object, the attempt to make or imitate gold; consequently, the many interesting substances that they must have discovered in their researches remain unrecorded

The best known figure of Alexandrian Alchemy is Zosimus of Panopolis (*c.* A.D. 300) who wrote an Alchemical Encyclopædia in 26 books, of which many fragments remain. The most curious feature of Alchemy throughout its life of sixteen hundred years is the symbolic and religious treatment it gives to a problem which appears to us to be a purely material one. Alchemy is always treated as a secret and traditional art; its materials and methods are concealed by symbols. Undoubtedly it was regarded as a divine and sacred Art, perhaps because it partook of the creative power, otherwise the prerogative of Deity.

The conversion of base and imperfect materials into the most perfect, beautiful, and indestructible of metals was a symbol of the regeneration of the base faculties of man into a new and divine nature, and it is certain that some alchemical texts are related to practical chemistry, only, in the phrase of Silberer, in the same manner as freemasonry is related to practical building.

THE DECLINE OF INTEREST IN SCIENCE, A.D. 300–700

The enthusiasm of the learned for Natural Science became replaced by an even more intense devotion to mystical philosophies and to religion. The tendency begins in the century succeeding the birth of Christ, and after about A.D. 250 little was written on science, save commentaries on earlier works.

In these years some of the world's greatest mystical philosophers flourished. Among the pagans, Plotinus (*d.* A.D. 270), Porphyry (A.D. 300), and Iamblichus (*died c.* A.D. 330), regarded the mystical perception of

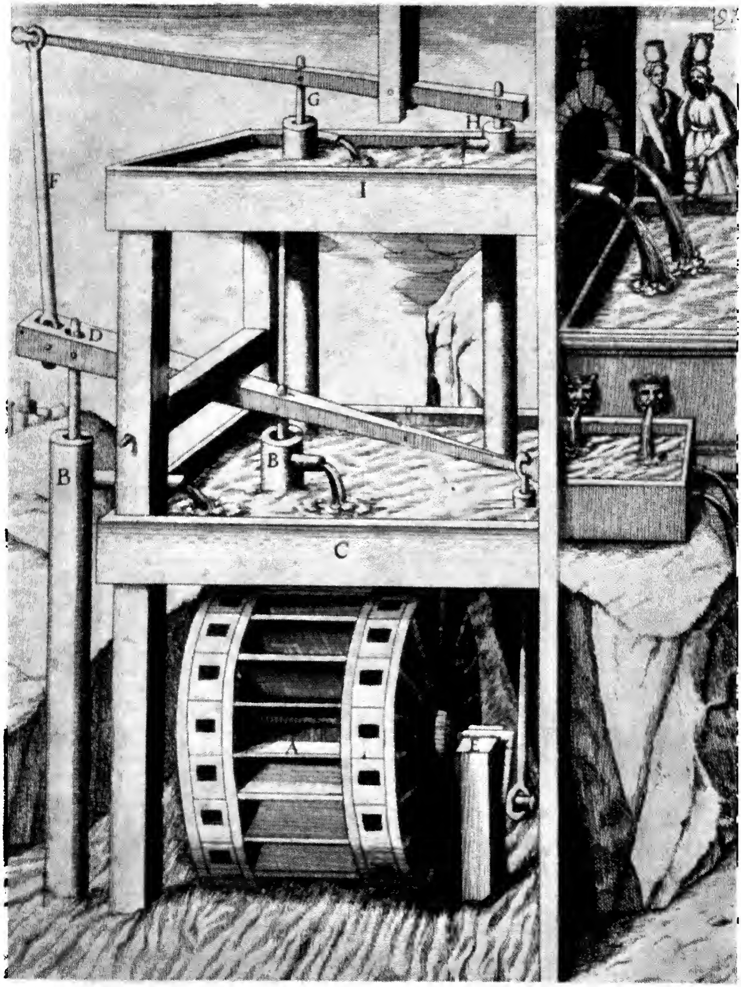


PLATE I
The use of water power for raising water. The inefficiency of machines such as this was the chief cause of the development of the steam-engine. (*Theatrum Machinarum*. Böckler. 1662.)

PLATE II

A Chinese salt-works, as depicted in a work on *materia medica*. Sea-water is evaporated in open pans, the salt-crystals fished out with baskets, drained and stored.

(1)

(2)

(3)

PLATE III

The development of the oldest craft—flint-working. The implements shown are (1) an Eolith, typical of the dawn of human craftsmanship. (2) a Palaeolithic hand-axe, typical of the old Stone Age (perhaps 20,000–40,000 years old). (3) a Neolithic dagger, typical of the age immediately preceding the general use of metals (*c.* 500–10,000 B.C.).

Deity as the highest purpose of man. They were not far different in spirit from the Christian philosophers who, however, tended to despise all learning which had not a religious purpose. Saint Augustine (354–430), who was a follower of Plotinus before he became a Christian, was, perhaps, intellectually the greatest of the Christian Fathers. His views on Natural Science are interesting:

> "It is likewise commonly asked of what form and figure we may believe the heavens to be, according to the Scriptures. For many contend much about those matters, which the greatest prudence of our Authors has forborne to speak of, as in no way furthering their learners in respect of a blessed life, and, above all, as taking up much of that time which should be spent in holy exercises. For what is it to me whether the heavens, like a sphere, surround on all sides the earth, a mass balanced in the middle of the world, or, whether like a basin they only cover or overcast it?"

The possession of secular learning was even regarded as disgraceful by some Christian saints such as St. Gregory the Great (*c.* A.D. 600).

In the West knowledge of Greek became the rarest of accomplishments, and the Greek scientific learning became almost entirely extinct. But in the city of Byzantium, or Constantinople, which had become the seat of the Roman Empire in A.D. 330, Greek learning remained alive but sterile for more than a thousand years. In the near East the next revival of learning occurred in the eighth century A.D. when

the treasures of classical learning came into the hands of the conquering Arabians.

From the fourth to the eighth centuries science was dormant in the West: we may, therefore, pause to examine the beginnings of science in India and China.

CHAPTER III

EASTERN AND ARABIC SCIENCE

SCIENCE IN EARLY INDIA

WHILE the great advance was being pressed forward in Europe and the near East, two largely independent civilisations were evolving in India and China.

The beginnings of Indian civilisation are hardly less ancient than the Egyptian, for the remains from Mohenjo-Daro in the Indus valley must date from about 3000 B.C. Of this early civilisation no written records have been deciphered. About 1200 B.C. the Indus valley was invaded by the Aryans, and the earliest records of Indian literature, the Vedas, date from about 1000 B.C. The dating of the earlier Indian literature is difficult: it is quite certain, however, that a high state of intellectual development existed between about 700 B.C. and A.D. 500. In Sanskrit, the Indians had a language capable of expressing with accuracy the most subtle shades of meaning. The Indian genius was psychological, and no other people has evolved so systematic a vocabulary of terms for the expression of states of mind. The Indian philosophers were essentially intuitive and introspective; they early perceived the illusory character of sense-perceptions and so attached far more value to the results of inner vision, or of reasoning, than to external observations. The first Indian philosophical system may have come into being at

much the same time as the beginnings of Greek philosophy, namely, between the eighth and fifth centuries B.C. The *Upanishads* show us an uncompromising assertion of the unity of all things as manifestations of Brahman, a conception which cannot be explained in a few words, but is allied to that of a universal God or World-Soul. It follows, then, that matter in its diversity, as perceived by human faculty, is an illusion (*maya*); we shall not expect from the holders of such beliefs any great interest in Natural Science.

The Sankhya philosophy developed at much the same period. Its view-point is rational and less idealised than that of the Upanishads. The existence of a God is denied, but real matter and an infinite multitude of individual souls are the constituents of the universe. Matter is composed of three substances (*guna*), analogous to the elements of Aristotle. The first of these, *Sattva*, contributes light and joy, *Rajas* movement and pain, and *Tamas* heaviness and sloth. The disequilibrium of these three principles was thought to result in the evolution and devolution of an infinite series of universes. The whole of the Indian philosophy is far sundered from the practical: consequently we find that only in the realm of mathematics did the Indian genius make a valuable contribution to world-science as we conceive it to-day.

The Hindu theories as to the nature of matter were generally metaphysical, though at an early period they developed a well-reasoned atomic theory. In general, however, they were concerned rather with the essential nature of matter, mind and spirit, than with the constitution of matter or its physical behaviour. The modern attempt to separate the thing observed from the observer was foreign to them; they early realised that the knower, the

thing known and the knowledge were interdependent and strictly speaking inseparable. No doubt the Indian attitude of considering knowledge both in its subjective and objective aspects is ideal: but the success of science has only been possible because it has shelved the insoluble philosophic problems of the nature of thought and perception, and has concentrated on the aspects of natural objects—length, mass and time—which are measurable by processes requiring the least possible intervention of the individual mind. Like the Greek, the Indian felt that nature must be symmetrical and perfect; if his observations did not harmonise with perfection, he trusted his ideas rather than his eyes. But, where the Greeks sought for simplification and unity, the Indian tendency was to complexity and multiplication.

Indian medicine and anatomy illustrate this well. It seems quite certain that the human body was dissected, yet the accounts of its anatomy in Indian works are grossly in error. Thus it was believed that the body contained ten systems of ducts bearing the ten fluid products of the body to all portions of it. The reasoning appears to be that ducts and fluid products were observed. Ten was considered to be the perfect number. The anatomists, therefore, sought for, and believed they had found, structures which agreed with the philosophers' notions of perfection.

Indian medicine, considered as a science, was defective. It had, however, a large armoury of drugs, many of which seem to have been potent. Great reliance was placed on charms, which, no doubt, were most effective. The psychological powers and receptiveness of the Indian are so great that a spell had far more chance of success in curing an ill-diagnosed complaint than had drugs or the knife.

The Indian philosophers had little knowledge of physics. It is thought that they practised some form of alchemy (probably after A.D. 500), but there is no evidence that their chemical achievement reached that of the Greek alchemists.

The quality of Hindu astronomy was curiously uneven. There is evidence that the astronomical observations of India go back at least to 1400 B.C. Their knowledge of solar and planetary motions was poor compared to that of the Greeks, but they had recorded the progress of the moon through the sky with an accuracy which was not surpassed until the seventeenth century. They developed a mathematical technique for observing these motions and were the originators of the trigonometrical tables of sines of angles; these they introduced to the Arabs.

The real merit of the Indian scientific culture is to be found in its mathematics. The Indian genius tended towards arithmetic and algebra rather than geometry. The mechanism of argument and formal proof by which the Greeks permanently established their knowledge did not interest the Indian authors, who, for the most part, have stated correct results without proof. Some of their geometrical results are of very great accuracy. Thus in the Sulva Sutras, of uncertain date, but probably earlier than the third century B.C., the ratio of the diagonal of a square to its side ($\sqrt{2}:1$) is given thus: "Increase the measure by a third part and this third by its own fourth, less the thirty-fourth part of that fourth." This gives $\sqrt{2}$ as

$$1+\frac{1}{3}+\frac{1}{3\times4}-\frac{1}{3\times4\times34}=1.4142156$$

$$\text{the true result being} \qquad =1.414213\ldots$$

Such accuracy could not be attained by measurement, as the error is equivalent to only 1/3 of an inch in a diagonal

a mile in length! Possibly some calculation by a method of trial and error was employed. Again the value of π is given thus (fifth century A.D.): "Add 4 to 100, multiply by 8 and add 62,000, the result is approximately the circumference of a circle of which the diameter is 20,000." This gives 3.1416 . . . a value correct to five significant figures. This result may have been reached by measurement, but it is to be remembered that Greek geometers, considerably before this date, had evolved methods of approximating to π.

The chief mathematicians were Arya-Bhatta (*b.* A.D. 476), who appears to have been a geometer and astronomer, Brahmagupta (*b.* A.D. 398), who compiled accurate astronomical tables, chiefly for use in astrology, and Bháscara (*c.* A.D. 1150), who wrote remarkable works on arithmetic and algebra. In the writings of the latter we find the modern system of expressing numbers by position and the use of a zero. He describes all our ordinary arithmetic, including square roots, cube roots, fractions, rule of three, problems about interest, etc.

His algebra is not expressed in the same manner as ours, but a little thought enables us to see that he is performing the same operations. For the unknown quantity he puts *ya* where we put *x*; *ya* stands for *yavat-tavat* or "so much": for other unknowns he puts "black, blue, yellow, red," etc., where we put *a, b, c, d,* etc. His examples are set out with more words and fewer symbols than are ours. He showed how to solve simple and quadratic equations—finding both roots—arithmetical and geometrical progressions, indeterminate equations of the first degree, permutations and combinations, etc. Later Indian authors did not advance beyond Bháscara until modern times.

The influence of the Indian mathematicians on the Arabs is difficult to assess. The latter certainly gained mathematical knowledge from India before they had access to any of the great Greek mathematical authors. This influence does not seem to have developed and, as time went on, so the tendency of the Arabs to revert to the Greek methods became more marked.

CHINESE SCIENCE

The Chinese culture arose at an exceedingly early date, which may be in the region of 3000 B.C. There are legends of a golden period of progress somewhere in the third millennium B.C., but no reliable historical records remain. The genius of the Chinese has not proved itself a scientific one, though from the earliest times they have excelled in the arts and technology.

Chinese astronomy was carried on from the earliest period, but consisted, like that of Egypt and Babylon, mainly of carefully recorded observations of eclipses, positions, etc., and the compilation of very detailed star-maps. Little attempt seems to have been made to deduce from these findings a model of the cosmos, such as the Greek system of revolving spheres. There seems to be evidence that an eclipse was observed as early as 2136 B.C., but careful and systematic records begin from 611 B.C. The length of the day was determined as 365¼ days at a period which is thought to have been as early as 2000 B.C.: if this is true it constitutes a remarkable feat. It would appear that the Chinese observing instruments, such as graduated circles, were decidedly in advance of anything constructed in Europe before the fifteenth century.

The great period of Chinese mental activity—the age of Confucius and Lao-Tse—coincided more or less with the rise of Greek and Indian philosophy. But the Chinese genius was not adapted for inquiry into nature, but far more to a right disposal of life to grace and dignity. Hence the technology of such arts as ceramics was developed to an extent still unsurpassed, while the pure sciences made little progress. Astronomical observations prospered as handmaids of astrology and religion, for it was a prime belief in China, as indeed all over the world, that the stars exerted a directing influence upon man. As time went on, the Chinese developed a complex system of the world, based on a dualism, in which all things were informed by positive and negative principles, *yang* and *yin*; these may perhaps be thought of as corresponding respectively to energy and matter, to soul and body, to male and female. But speculations and reasonings based on this theory were fatal to Chinese science, for it was easier and more congenial to their philosophers to evolve a false science *a priori* than to deduce the truth from laborious observations. Chinese science finally became purely traditional, the ancient books having an absolute authority.

Chinese medicine and surgery reached no high level. A very ancient medical work has been ascribed to the Yellow Emperor (2698–2598 B.C.). The attribution and dating of this are, of course, legendary, and, like other early Chinese medical and surgical works, it belongs to a period later than 500 B.C. The distinctive feature of their diagnostic methods was an elaborate observation of the pulse, of which, however, they did not understand the cause. No doubt a skilled physician who made a minute study of the pulse would attain by observation and memory a fair degree of diagnostic skill; but even so the methods of

treatment were quite inadequate. Their chief surgical remedies were superficial cautery and acupuncture, the insertion of fine needles into the ailing member, a practice which may have sometimes provoked a useful physical reaction and had some psychological value. They noted 367 points where these needles could be inserted without causing injury, showing thereby some anatomical knowledge. The Chinese had quite an extensive knowledge of *materia medica;* a sixteenth-century work, which derives from much earlier sources, lists 1892 drugs, many of which were of much value, though most were totally inactive.

In China we hear for the first time of the scientific observation of earthquakes, and a simple seismograph was invented by Chang Heng in A.D. 132. His instrument was a copper vessel to which were attached eight dragon-heads, having in each of their mouths a delicately poised copper ball, which any slight vibration would cause to fall into the mouth of a copper toad below. Since the particular ball which fell would be the one in the path of the seismic wave, the place of the earthquake could be predicted. One distant earthquake, at least, was detected by its aid, though nothing could be felt; its confirmation by messages, received some days later, made a great impression.

Alchemy was practised in China, and there seem to be records of attempts to transmute metals as early as 200–100 B.C. The texts are very obscure, but it appears that the techniques of crystallisation and sublimation were known, though at present there is no evidence that distillation was practised. The main object of Chinese Alchemy was to gain, not wealth, but immortality. The Chinese did not employ gold as currency. They believed,

however, that it was a material peculiarly rich in *yang*, the principle of soul as opposed to matter. They thought that cinnabar (vermilion) was also very rich in *yang*, and that if cinnabar could be converted into gold, a material of peculiar life-giving potency would result and could be used to make the "pill of immortality." It is interesting that the Alexandrian Alchemists (p. 62) knew nothing of an Elixir of life, nor yet of a Philosophers' Stone in the sense of a substance, a minute amount of which would transmute to gold or silver a great portion of base metal, but that both these ideas occur in the Chinese and Arabic alchemical works; this fact suggests a connection between these latter, perhaps with India as an intermediary or common source.

The influence of India on China was, of course, considerable. Great numbers of Buddhist monks and teachers migrated to China and brought with them much of the Indian knowledge and especially their mathematics. But a culture cannot be transplanted into an unfavourable soil; and the Chinese mathematicians never reached, far less surpassed, the standard of their Indian teachers.

ARABIC SCIENCE

The late Greek culture was not confined to those who spoke Greek. In the near East were many centres of learning in which the works of Aristotle, Archimedes, Galen and many others were translated into Semitic tongues. The Nestorian Christians translated many of these works into Syriac, the colloquial form of Hebrew then in use.

The Emperor Zeno regarded the Nestorians as heretics

and banished them in A.D. 489. They fled to Persia, where the Sassanid rulers made them welcome and so created a school of Greek learning in Persia. The medical school at Gundi-shapur in East Persia seems to have preserved much of Greek science. Later, about A.D. 500–700, the Monophysite Christians made further translations from Greek into Syriac. These translations were of the greatest importance as being the means of transferring the learning of the Greeks to the Arabs.

When Mohammed began his work Arabia was peopled by disunited tribes. He formed a united Arabia and inspired it with a religious fervour for conquest. Mohammed died in A.D. 623, but his successors, the early Caliphs, carried on his work. By A.D. 641 the Caliphs Omar and Othman had subjugated Persia, Iraq, Syria, Egypt with the North coast of Africa, Armenia and Asia Minor. In 658 the Omayyad dynasty was established in Damascus, where the first impulses to learning stirred again. Later the capital was transferred to Baghdad, where, under the Abbasids, culture and learning reached a high level. During the eighth and ninth centuries, Nestorian Christians were notable as physicians in Baghdad and gave to the Arabs the culture they had themselves gained from the Greeks. The Caliph Mamun (reigned A.D. 813–833) gave his great authority to this quest for learning. The story is told that he saw in a vision the venerable figure of Aristotle seated on a throne, and consequently sent a deputation to the Byzantine Emperor, Leo the Isaurian, to obtain scientific books for translation into Arabic.[1] The scientific works of Aristotle, Ptolemy, Galen, Archimedes and some others were accordingly translated (with no great accuracy) into

[1] Nicholson. *A Literary History of the Arabs*, 1907, p. 359.

Arabic; and, indeed, a few Greek works are known to us only from Arabic versions. The "venerable figure of Aristotle" seen by Mamun is typical of Arab learning. The ancient Greeks seemed to them to be more than human—bearded sages or magicians wrapped in the mist of centuries. The Byzantines had already begun to treat Aristotle and Plato as almost unassailable authorities. The Arabs made them into venerable Magi: Europe in later years treated them as hardly less than inspired. The paralysing effect of an absolute scientific authority began in the Arabic culture and finally became intolerable in sixteenth-century Europe.

The new discoveries of the Arabic world were few: the Arabs must be looked on as preservers of knowledge rather than originators of it. They absorbed foreign ideas with astonishing readiness and their assimilation of Greek culture was a fine achievement; none the less they originated no single great conception. The Moslem theology regarded all events as direct acts of God, a view which denied scientific law and made the miraculous credible. The scientific world-view was, therefore, somewhat foreign to the Moslem genius and, as might be expected, a great number of the men of science who flourished under the Arabs were not of Arab blood, but were Syrians, Persians or Jews.

Southern Spain was conquered in the eighth century and became a centre of culture. The Moslem enthusiasm for learning was immense. Schools were founded in almost every town they conquered, and such great centres as Baghdad, Cairo, Toledo, and Cordova, had universities equipped with observatories, laboratories, and fine libraries. It is related that Hakam II (961–976) had in his library at Cordova no less than 600,000 volumes,

the catalogue of which consisted of 44 volumes; in contrast to this enlightened condition we may note that the royal library of France 400 years later consisted of about 900 volumes. The fusion of Jew, Spaniard and Arab made southern Spain an area where Christian and Moslem culture met. Sicily too, was conquered by the Arabs and from A.D. 878 to 1061 was a centre where somewhat similar conditions prevailed. In Toledo a large Jewish, Spanish and Arab community became unified, both Spaniards and Jews adopting the speech and habits of the Moslems. Toledo was recaptured in A.D. 1085 and remained a Christian salient surrounded by Arab territory. A College of Translators was set up there and a series of very indifferent Latin translations gave some of the Arabic culture to the Christian world.

ARABIC MATHEMATICS

In Mathematics the Arab's main achievement was the development of arithmetic and algebra, though even here the greater part of their achievement derived from India and Greece. We know that in 772 a Hindu astronomer introduced trigonometrical tables of sines of angles to the court of the Caliph Al-Mansur, and it must have been in the eighth century that there came into use the Hindu numerals, the zero, and the notion of the position of a number determining its value. There is a good deal of doubt whether the Indian numerals were not used in Rome at a much earlier date, but the zero, without which the simple modern positional system of computation could not be used, was not brought to the Western world before the Arab period. Hovarezmi (Muhammad b.

Musa al-Khwarismi, *c.* A.D. 825) wrote a work on algebra and arithmetic, in which the latter appeared for the first time in a recognisably modern dress. His algebra seems to have been derived from both Indian and Greek sources, but it contains a certain amount of new matter. The word *algebra* is the Arabic *Al-djabr*, which means the removal of negative quantities from an equation by transferring them to the other side of the equation so that they may become positive. Thus $x^2 + 5x = 20 - 3x$ is transformed by Al-djabr to $x^2 + 5x + 3x = 20$. The algebra of Hovarezmi amounts only to the elementary operations of addition, etc., and the solution of linear and quadratic equations.

At this early period the Arabs had not obtained fully intelligible translations of the Greek geometrical works, but between A.D. 800 and 900 they assimilated all the Greek mathematical knowledge. In fact, the more powerful algebraic methods of the Indians were neglected in favour of the Greek solution of problems by geometry. Tables of tangents of angles were brought into use; great improvements in spherical trigonometry were made, which rendered easier the study of astronomy. Most of the Arab mathematical works were the product of the Eastern Kingdom, but the Arabs in Spain produced one great astronomer-mathematician, Gabir-ben-Aflah,[1] who lived somewhat before A.D. 1100. He made original discoveries in trigonometry, but still neglected the Indian methods.

[1] Often known as Geber. He is not identical with the alchemist Geber. The word *algebra* was formerly thought to be derived from his name, but this view is now discredited.

ARABIC ASTRONOMY

In astronomy, also, the Arabs, while they studied extensively, made little advance on the Greeks and did not put forward any view of the cosmos better than that of Ptolemy. They built larger and more accurate instruments, made many and careful observations, calculated yet more accurate sets of astronomical tables, but found out no new principles. It appears that some astronomical knowledge reached the Arabs from India. Astrology, which had been so prominent a feature of Babylonian astronomy, but which had declined in importance under the Greeks, was greatly cultivated by the Arabs. Their belief in the divine direction of affairs made astrological predictions seem very credible, and the munificence of the Caliphs in erecting observatories was no doubt in part inspired by a practical wish to learn the future by their aid. The debt the world owes to the Arabic astronomers is in respect of their preserving Greek learning and transmitting it largely intact and in some respects improved, to Christian Europe. It would be beyond the scope of this book to recount the names of the astronomers of this period, but one of them is known to all of us, the Persian Omar Khayyám. No less gifted as mathematician than as poet, he wrote a brilliant work on the solution of equations, and in astronomy did valuable work on the adjustment of the calendar.

ARABIC CHEMISTRY AND PHYSICS

The problem of Arab Chemistry is an obscure one. The Greek chemists or alchemists described the elements

of chemical technique before A.D. 300. Some of their works were certainly translated into Syriac. There are some hundreds of Arabic works on Chemistry and Alchemy, but very few indeed have been translated into a European tongue. On the other hand several important Latin works are known which purport to be translations of Arabic Chemical works, but apparently lack originals. It is difficult, then, to assess the Arab contribution to Chemistry. It would seem, however, that we owe to them the discovery of borax, sal ammoniac, nitre, nitric acid, sulphuric acid, silver nitrate, ammonia, perhaps alcohol, and a number of other chemical compounds. The Arabic article is preserved in the words alchemy, alembic, etc. The first of these epitomises the early history of Chemistry, for it is derived from *al,* the Arabic article, and a Greek word for Chemistry, *chemia,* which is itself probably derived from *Khemia,* a word for Egypt, wherein the science or craft of Chemistry first arose.

In their theory of matter the Arabs on the whole followed Aristotle. They thought of matter as a continuous blend of "elements," not as a mixture of atoms, though the atomic view was not unknown to some of them. It was commonly believed that the seven metals were varieties of a single kind of matter and so could be transmuted one into the other. Thus to quote the geographer Kazwini:

> "The alchemists say that tin is a silver suffering from leprosy, mercury a silver struck with paralysis, lead a leprous and burnt gold, and copper a crude gold, and that the alchemist, in the manner of a doctor, cures the diseases by means of contrary or similar principles."

The belief in Alchemy was, however, far from universal and the possibility of transmutation was hotly argued.

Physics made some progress. The idea of specific gravity, introduced by Archimedes, was further developed, and apparatus was devised for measuring it by weighing a solid in air and in water, and also by weighing the water which was caused to overflow from a vessel by addition of a body of known weight. In Optics, too, much progress was made by Alhazen (965–1020) who worked out the theory of spherical and parabolic mirrors, and also studied lenses. He treated optics mathematically, and the Latin translation of his works remained the standard optical textbook in Western Europe until the seventeenth century.

ARABIC MEDICINE

The Arabs gave a high place to their physicians, who were usually of another race, Persian, Jew, or Syrian Christian. They made very few original contributions to medicine, but kept alive the knowledge of the Greeks and added a little to it. In the Eastern Caliphate, Rhazes, Haly Abbas and Avicenna (to use their Latinised names) wrote voluminous works almost entirely taken from the Greeks. These works, though for the most part not original, were of the greatest importance; for some of them, such as the *Canon* of Avicenna, were excellent systematisations of what was then known, and, in Latin translation, they served Europe in the Middle Ages as standard medical textbooks. A small amount of new matter appears; Rhazes wrote a work on small-pox and measles which seems to be original. The Arabs improved the *materia medica* of the ancients, introducing mineral preparations such as mercurial

ointment, and also a good many exotic drugs.

It would be unjust to so great a man as Avicenna to let him pass merely as a codifier of other men's medical learning. His life may serve as a picture of that of a great Arabian scholar. Avicenna was born in Persia in the year 980. By the age of 10 he knew the *Koran* by heart. He learnt from a greengrocer the elements of arithmetic, and from a wandering scholar gained a knowledge of more advanced mathematics. By the study of books which he bought for himself, he acquired a knowledge of Logic, Geometry and the *Almagest*. He then studied and mastered medical theory and was an active practitioner at 16. He studied Aristotle deeply, and is said to have persevered in reading his *Metaphysics* forty times, but to have failed to understand it until a commentary of al-Farabi enlightened him; whereupon in joy he gave alms to the poor. He spent his life in Persia as royal Physician and, at one time, as Vizier to an Amir. He wrote about a hundred books ranging through almost every department of learning—theology, philology, mathematics, astronomy, physics, music and medicine. Yet he was no dusty scholar and was addicted to the good things of life, dying at the age of 58 as the result of a bout of pleasure.

The Arab genius was throughout its course restrained by its respect for the ancient Greek authors. The Arab was scholarly and learned: he preserved and absorbed every fragment of foreign knowledge, but he lacked the brilliant originality of the Greek. The Arab ideal was the learned sage who knew: the Greek ideal was the thinker who *a priori* could deduce the laws of a universe. Science could make little progress until Greek reasoning, Arab learning and European experimental testing of facts were united into a scientific method.

CHAPTER IV

MEDIÆVAL SCIENCE

THE AGE OF IGNORANCE, A.D. 500–900

WHILE the Arabs were greedily absorbing all the knowledge of the East and West, learning in Western Europe touched its lowest depths.

Between A.D. 500 and 900 scarcely a flicker of the ancient learning illumined the Western world. Despite the fact that in the Moslem countries science was active, and that the Byzantines retained the philosophy of ancient Greece and thought in terms of it, the newly civilised Germanic tribes, who were the masters of Europe, remained in almost total ignorance. The disappearance of the knowledge of the classical world and the small desire of the Western world for learning may be traced in part to the lack of stable political organisation. It was as much as men could do to feed themselves and protect themselves from their neighbours. Amid the destruction of the political and social institutions of the Roman world, the new organisation of the Christian Church stood strong: she alone could give that measure of safety and tranquillity which a learned life requires. The intellectual life was lived wholly within the boundaries of the Church: naturally then, religion was the subject and object of the learning of the age. The new religion at first regarded pagan history and philosophy as useless knowledge, and consequently there survived only such scraps of these as

might assist or illustrate religion. The genius of the age was not a learned spirit. The minds of the new possessors of Europe could have nothing in common with those of Greece and Rome. An uncritical acceptance alike of Christian doctrine, fairy-tale legend, and a few scraps of classical lore, was the highest intellectual achievement to be expected of the centuries between A.D. 500 and 900.

The darkest period of ignorance was bridged by certain Christian writers who summarised—in small enough space—the scanty science of their time. Cassiodorus was a statesman, monk, and man of learning, who lived in Italy from A.D. 490–580. He compiled an encyclopædia of the knowledge of his time, which was drawn on by the more famous Saint Isidore of Seville. Isidore lived between A.D. 600 and 650 and wrote, in addition to numerous theological works, a compendium which contained, as a contemporary said, as much as a Spaniard of the Dark Ages ought to know—i.e. about as much as, wordily expressed, would fill a 300-page book.

Isidore's work gives a curious picture of the mind of the time. He is much more interested in etymologies and definitions than in the things he describes. He is content to copy out scraps of older authors, without giving any consistent view of his own: thus he treats the earth as round in one sentence, but implies it is flat in the next.

Isidore's universe has a central earth, probably thought of as flat, surrounded by a revolving sphere carrying the stars; he also had some notion of the Greek conception of inner planetary spheres. We meet in Isidore the small universe of the Middle Ages: only a few thousand miles in extent, only a few thousand years old, and destined soon to perish. Isidore's view of matter is a corrupted form of Aristotle's four-element theory.

The transfiguration of the mathematics of the Greeks is remarkable. St. Isidore's arithmetic is simply a discourse on the mystical properties of numbers. It is abstracted from an author who took his matter from another author who had drawn on the work of the Alexandrian writer Nicomachus (A.D. 100)! As for geometry, all that St. Isidore can give us is a few definitions of planes, circles, cubes, etc. His accounts of medicine, anatomy, physiology and zoology reach a level but little higher.

The Venerable Bede, born at or near Jarrow in 672 or 673 (*d.* 735) is best known to us as a religious historian. He left a short account of the sciences which amounts to little more than that of St. Isidore. This slender stream of learning descends through the authors Alcuin, Hrabanus Maurus, and Honorius, until it is merged in the wider waters of the revival of learning in the twelfth century.

The temper of Christian science is well illustrated by the *Physiologus,* a work which purports to be a natural history. It probably originated in the Christian community of Alexandria in the second century A.D., for its stories are quoted by the Fathers of the Church. The book is even to-day exceedingly amusing reading. It contains accounts, almost entirely fabulous, of the habits of animals. The truth of the contents of the book was wholly unimportant to the writer and readers, for their object was to draw moral lessons, and not to study animals. The story of the Ant-lion is typical. He has the countenance of a lion and the hind-parts of an ant. His father is a flesh-eater, his mother a plant-eater: consequently it is against his nature to eat either flesh or plants, and he perishes for lack of food. So likewise has every man a double spirit contrary in all its ways. . . .

The *Physiologus* was one of the world's most popular books. It was translated into almost every language and its queer beasts are carved in hundreds of Gothic churches. Its popularity was due to the mediæval taste for marvels and moral reflections. Plates IV and V give a good idea of its character.

The medical works which were written in Western Europe in the period between the end of Greek science and the beginning of the revival of Medicine in the twelfth and thirteenth centuries have no value as science, but are interesting as reflecting the temper of the age. The Anglo-Saxon leech-dooms are quite extensive medical treatises. We find in them elements of Greek and Latin medicine and pharmacy, but, which is of more interest, a great measure of native magic. These works are mainly based on a traditional folk-medicine without any scientific basis. Diseases were supposed to be caused either by venoms which could travel through the air and blast the body, or by worms lodged in the affected part, or by arrows shot by malicious beings or elves. For diseases of such origin spells were obviously more valuable than drugs, and were naturally much in use.

THE SCHOOL OF SALERNO

It must be remembered that while primitive spells and crude drugs were being used by Teutonic leeches, utterly ignorant of anatomy and physiology, the Arabs were at the height of their medical prowess and had the heartiest contempt for the crude methods of the Franks. It is not surprising then, that when Arab and Frankish culture met, there arose a school of medicine dependent on both.

At Salerno near Naples, at a period not far from A.D. 100, the first European university developed. A Jewish medical man, Shabbethai Donnolo (913–984), wrote a medical treatise based on Arabic medicine and his work seems to have been the origin of the medicine of Salerno. Constantine the African also translated certain Arabic medical works, incidentally appropriating the credit for their authorship. From the eleventh to the thirteenth century, Salerno produced many notable physicians, whose work is a continuation of the Arabic and Greek tradition; their works were later translated into French and had the greatest influence on medical progress.

BYZANTINE LEARNING

The utter disappearance of scientific knowledge in the West was due in great part to ignorance of the Greek language. As we have already seen (p. 40) the centre of Greek culture in the first three centuries of the Christian era was Alexandria. The city of Byzantium was already a thousand years old when, in A.D. 330, the emperor Constantine transferred to it the seat of Empire. When Alexandria had succumbed to the Moslem, and the Emperor Justinian in 529 had closed the ancient schools of Athens, Constantinople kept alive the knowledge of the ancient world. But as in the West, so in the East, the learned Christian was preoccupied with theology, and the Greek interest in science and philosophy for their own sakes was almost dead.

Medicine was well cultivated in Byzantium and there seem to have been a few small additions to the knowledge of the ancients, but substantially the Byzantine scientific

authors were content to copy and comment on their forerunners without much attempt at originality.

The sack of Constantinople by the Crusaders in 1202 almost put an end to the Greek culture which still flourished there. There survived, however, a great treasure, namely, the manuscripts of Greek authors and the knowledge of classical Greek, a knowledge which after the fall of Constantinople to the Turks (A.D. 1453) was to set Europe alight with learning.

THE REVIVAL OF LEARNING IN THE WEST

From A.D. 1000 onward the beginnings of a more active desire for knowledge appeared in the West. Early in the eleventh century we must put our first English aeronaut, the monk Eilmer. He had a reputation for learning, especially in astrology and mechanics. We are told that he fitted wings to his hands and feet, and flew from the top of a tower for more than a furlong, before falling to the ground. He was lamed but not killed, and attributed his fall to the fact that he had omitted to furnish himself with a tail. There seems no reason why the attempt should not have been made, though we must doubt the furlong's flight.

The twelfth century marks the beginning of a great intellectual period in the history of England, when our country gave birth to some of the greatest men of the age: Alexander Neckam, Roger of Hereford, Michael Scot, Robert Grosseteste, Roger Bacon and Gilbert the Englishman.

Earliest of these was Alexander Neckam (*b.* 1157). His

career was remarkable from the start, for his mother suckled him at her left breast and Richard Cœur-de-Lion at her right. No doubt his royal foster-brother aided his advancement. At the age of 23 we find him Professor in the University of Paris. He compiled an encyclopædia of the sciences, which, while of no high level, manages to free itself from a wholly slavish adherence to his forerunners. He adds a good deal to the information handed down by Isidore and his followers; stories of animals—mostly fabulous—interest him greatly and he has some useful work on optics. Of great interest is the mention of the mariner's compass, which he is the first to describe. The first compasses were made by stroking a needle with a natural lodestone, so magnetising it; the needle was then stuck into a straw or a cork and floated on water. But the invention of a pivot compass soon followed, and indeed Neckam alludes to it. Neckam seems to have had little or no knowledge of Arabic science. It is interesting that in a long section devoted to gold he makes no allusion whatever to alchemy, which probably did not reach this country until the early thirteenth century. While Neckam undoubtedly made some new contributions to written science, a great part of his work is occupied with wordy and pious discussions. The following extract from his book *On the Natures of Things* illustrates the two vices of mediæval science, namely its credulous acceptance of untested reports, and its tendency to use natural phenomena simply as moral lessons.

"*On a spring which increases if a red cloth come near it.*

"They say there is a spring which undergoes a sensible increase as often as any one clad in a red garment comes near it. Many have laboured to assign a cause why this

should happen, putting forward new and useless fictions. For they say that like rejoices in like. They consider that a spring welling up in red earth would boil over from the increase of redness. But the slenderness of this argument is not hidden from the intelligent. For who was the counsellor of nature in her work? But we are instructed morally concerning the event spoken of, inasmuch as familiar association with a wrathful man is much to be avoided. For minds formerly made peaceful are sometimes perturbed on the approach of such a man being incensed with anger. So I compare it to the redness of anger. One may rather understand also by redness the fervour of charity, by the happy approach of which human minds receive the increment of spiritual gifts. Nor should you wonder if I designate by the term water, now wisdom, now the human mind. They are different significances of the same thing."

Roger of Hereford (*fl.* about 1176–8) was our first English astronomer. He evidently had a knowledge of Arabic science and was able to make astronomical tables for the meridian of Hereford, based on the Arabic tables of Toledo and Marseilles. He wrote not only on astronomy but also on mines and metals.

Hildegarde of Bingen (1098–1179), one of the strangest figures of mediæval history, must take her place as one of the few women of science. Her work belongs to the Dark Ages and is not influenced by the Arab learning, which, a few years later, entered Europe as a fertilising flood. Hildegarde was a Benedictine nun, a woman of great mental power and mystical faculties. She had cisions of the universe, imagined in terms of Christian vosmology; this side of her achievement belongs rather

to religion than to science. Her visions are a strange blend of diagrams of the universe and symbolic pictures of God and the Soul: for the mystic these can coincide. In her study of human anatomy we find the same synthesis of Man and the Universe: to her, as to most mediæval thinkers, the secret of physiology was a correspondence between the organs of man and the outer universe of stars and planets, conceived of as living and active forces (pp. 107–9).

Hildegarde and Neckam lived too soon to receive the knowledge transmitted by Islam, but while they were living, the work of translation of this knowledge from Oriental to Occidental tongues had already gone far.

SCIENCE IN THE MIDDLE AGES

The Dark Ages showed little sign of clearing before A.D. 1000. In the years between 1000 and 1100 there was a stirring, between 1100 and 1200 rapid progress was made, and the thirteenth century must be regarded as one of the great periods of human mental achievement. This rapid progress in learning may be primarily set down to the more settled state of Europe. Stable systems of government had appeared; above all, international commerce had begun and was bringing wealth to the merchants of all civilised countries. This wealth found its way in great measure to the Church, which became an increasingly complex and potent organisation. In the protection of the Church, and by its patronage, scholars could live a learned life. But, for this very reason, science was less esteemed than in any previous great culture. The Greek man of science was a philosopher, the Arabian man of

science was a sage; the mediæval scientist was a "learned clerk", an ecclesiastic to whom all knowledge was necessarily comprised in and ancillary to a religious scheme. It is not in the nature of highly organised religion to admit uncertainty, for this leaves room for heresy. Accordingly the mediæval tendency was to create or compile complete schemes of the universe from the material found in such books as had unchallenged authority. The history of mediæval science is, therefore, chiefly that of the increasing means of study of classical learning.

From the seventh to the twelfth century scholars had access to only a pitifully small portion of ancient learning. Greek was unknown and only two works of Aristotle were available in Latin versions. These, with one or two works on logic, not of the best period, and the traditional knowledge handed down by Isidore and his followers, were all the scholars of 700–1150 could work on. From the last half of the twelfth century onward the ancient learning which had been preserved in Arabic was translated from that language into Latin by Gerard of Cremona, Michael Scot, Raimon Lull and many others. This work put the world in possession of much of the classical learning, especially the complete works of Aristotle and the commentaries upon them written by the Arabs. It is true that the texts had suffered considerably by miscopying and by translation, in some cases from Greek to Syriac, Syriac to Arabic, Arabic to Spanish, Spanish to Latin, but the flood of new knowledge was enough to inaugurate a new wave of learning.

Before about 1170 the only centres of teaching were monasteries and cathedrals. But from this date we begin to hear of the foundation of numerous universities, the most

notable of which were those of Paris, Bologna, Salerno, and in the thirteenth century, Oxford. The universities were, in a sense, guilds of teachers where the student, after a certain apprenticeship of study, received a degree, which was, in effect, a licence to teach. In the north the universities were almost wholly ecclesiastical, but in Italy there were numerous lay teachers. The subjects studied were the Trivium, i.e. Grammar, Rhetoric and Logic, and the Quadrivium—Arithmetic, Geometry, Music and Astronomy. Medicine was also studied, notably at Bologna and Salerno. The Quadrivium and Medicine made up a mediæval scientific education. What was learned was scanty enough. Science was comprised in the works of Aristotle and Euclid and the Almagest; Galen with Hippocrates and some Arab authors constituted Medicine.

Fig. 10, taken from a work published in 1508, is a symbol of the mediæval conception of learning. The student, after learning his alphabet, acquires Latin Grammar and Syntax from Donatus and Priscian. He proceeds to Logic, Rhetoric, Poetry, and Arithmetic, learnt from Aristotle, Cicero and Boethius. The next step is to study Music, Geometry and Astronomy. A further advance is the study of Physics and Morals, and the crown of learning is Theology or Metaphysics.

The new scholastic learning of the thirteenth century, the great men of which were Roger Bacon, Albertus Magnus, Thomas Aquinas and Duns Scotus, was little more scientific though much more extensive than the learning of the Dark Ages. Its exponents were clerics, brought up to think of the universe in terms of theology. Their keen and subtle minds appreciated Aristotle's logic and psychology: at the same time the doctrines of

FIG. 10

The Symbol of Learning. (From *Margarita Philosophica*. Reisch. 1508.) The upper stages of the student are represented by (1) Aristotle, Logic; Tullius, Rhetoric, Poetry; Boethius, Arithmetic. (2) Pythagoras, Music; Euclid, Geometry; Ptolemy, Astronomy. (3) Aristotle (Philosophus), Physics; Seneca, Morals. (4) Petrus Lombardus, Theology or Metaphysics.

Christianity were absolute in their authority. As we have seen, Arabic works on Aristotle were being translated in the twelfth century. The Arab Averroes who lived in Moslem Spain at this period had written a very famous commentary on Aristotle, in which he cut at the root of the mediæval system by denying the validity of theology and pouring contempt on the notion that human reasoning could enter into the sphere of spiritual imagination. The Church was therefore faced with a doubt as to whether the newly-found works of Aristotle should be condemned, and in 1215 this step was actually taken. But the great minds of the age could not allow the matter to rest there. St. Thomas Aquinas and William of Moerbeke, working in part on translations from Arabic and in part on translations directly from the Greek, succeeded in reconciling Christianity and Aristotle and in building a complete world-conception out of Christian doctrine informed by Aristotelian thought. St. Thomas Aquinas completed this edifice and his philosophy is still the official philosophy of the Catholic Church. Systems were evolved by which, it was believed, the various theological doctrines could be rigidly demonstrated to a doubting heathen; but not even to the mediæval philosopher could these for long remain convincing, and in the fourteenth century came a most important step, the doubt of the possibility of rational proof of theological doctrines. This could not in that age imply a general doubt of the doctrines themselves. Accordingly, the position was reached that, in the opinion of many, theological doctrines could not be proved by reason, but must be accepted by faith. The attempt to reconcile the Christian religion with philosophy, though officially accepted as successful, had in fact failed. A world of faith and a world of reason now

existed side by side, and the way lay open for a choice.

It is not easy to describe in words the way in which the facts of science were included in the philosophy of Aquinas. The following quotation which expresses his ideas concerning force and gravity shows at once the power and weakness of his outlook.

> "All things seek a *bonum* whether they have knowledge or not. To make this clear, we must know that some ancient philosophers supposed the effects of nature to arise from necessity of preceding causes, and not because the natural causes had a proper disposition for producing such effects. This the Philosopher[1] condemns in the second book of *Physics*, where he shows that if the relation and mutual utility of things were not in some way intended, they would happen by chance, and therefore would not happen in the greater part, but in the less, like all other things that proceed from chance. We must therefore say that all natural things are ordered and disposed for their proper effects. But a thing may be ordered and directed to another as an end in two ways, viz., either by itself, as when a man directs himself to the place whither he means to go, or by something else, as an arrow is directed to a given place by the archer. Now a thing cannot be directed to an end, unless the director knows the end. For that which directs must have knowledge of that to which it directs but things that know not the end may be directed to a given end. And this happens in two ways. For sometimes that which is directed to an end is only impelled, without receiving from its director any form to adapt it for this or that direction or inclination: and

[1] Aristotle.

such inclination is forced as an arrow aimed at a mark by an archer. But sometimes the directed or inclined thing has from its director or mover some form by which it is adapted for than inclination; and therefore such inclination will be natural, as from a natural principle. Thus He Who gave gravity to stones inclined them to fall naturally downward; and therefore it is said (VIII *Physics*) that the Maker of heavy and light things is also their Mover. In this way all natural things have an inclination to others that are adapted for them, having in themselves a certain principle of inclination, by reason of which their inclination is natural, so that these in a manner go of themselves, and are not merely led to their proper ends. But in forced movement things are only led or pushed not co-operating themselves at all with the mover, but in natural movement things go to their end inasmuch as they co-operate with the incliner and director by a principle given to them."[1]

The Middle Ages produced in science little or no advance beyond the achievement of Greece and Islam. Western Europe learned what these could teach her and at the same time learned to think. The scholastic learning was much concerned with precise subtle logic applied to theological matters which do not greatly interest us to-day, but the result of centuries of disputation was to endow the learned world of the West with logical habits of language and thought. During these years, too, learning was sowing its wild oats; creating points of difficulty for the sheer pleasure of feeling the power of its intellectual instruments. It was only when the limitations of book-learning and of reasoning from uncertain premises were

[1] *The Physical System of St. Thomas*. Cornoldi; *tr.* Dering, 1892.

realised by experience, that the world could settle down to collect a more certain knowledge.

Roger Bacon's (*c.* 1214–1292) was the one voice crying out against the emptiness of a system based on arguments lacking sound premises. He roundly condemns the scholars of his age for four faults: first, their dependence on unsound authority (though he himself regards the Holy Scriptures as an absolute authority); second, their yielding to established custom; third, giving weight to popular opinion; fourth, their concealment of real ignorance by a pretence of knowledge. He alone expresses the necessity for experimentally verifying conclusions reached by *a priori* argument; but even he regards argument from general principles, not from experimental results, as the natural way to arrive at a scientific conclusion.

The remaining men of science of the age were in complete dependence on authority. The medical men stated that where Aristotle and Galen agreed, there was complete certainty: where they disagreed, the mediæval doctor could hardly presume to decide.

The encyclopædists flourished exceedingly in the Middle Ages; some, such as Roger Bacon and Vincent of Beauvais, were very great men: lesser men wrote, for the less serious public, works in which the love of the marvellous is indulged to the full. These seem to the modern reader wholly delightful in their *naïveté*, but their value as science is negligible. Bartholomew the Englishman (*c.* 1260) only repeats other authors when he tells of the Siren.

"*Of the Siren.*

". . . And some men say, that they are fishes of the sea in likeness of women. Papias saith that Sirens be great dragons flying with crests as some men trow. . . .

Some men say that there are three Sirens some-deal maidens, and some-deal fowls with claws and wings, and one of them singeth with voice, and another with a pipe, and the third with an harp, and they please so shipmen, with likeness of song, that they draw them to peril and to ship-breach, but the sooth is, that they were strong hores that drew men that passed by them to poverty and mischief. . . ."

Both the legend and the interpretation of it appear in a popular book of *Sermons* by Honorius, a monk of Autun, who wrote about 150 years earlier. But when Bartholomew comes to write of the Cat, he gives us an artist's view, not a scholar's.

"*Of the Cat.*

"He is full lecherous beast in youth, swift, pliant and merry, and leapeth and reseth on everything that is before him: and is led by a straw, and playeth therewith: and is a right heavy beast in age and full sleepy, and lieth slyly in wait for mice, and is aware where they be more by smell than by sight, and hunteth and reseth on them in privy places: and when he taketh a mouse he playeth therewith and eateth him after the play: and is, as it were, wild and goeth about in time of generation. Among cats in time of love is hard fighting for wives and one scratcheth and rendeth the other grievously with biting and with claws. And he maketh a ruthful noise and ghastful when one proffereth to fight with another. . . ."

It is at least arguable that the emergence of knowledge from the domination of second-hand authority was in part

FIG. 11

Illustration of various beasts from Bartholomew's *De Proprietatibus Rerum*. The work was written about 1260: the picture is taken from an edition printed by Wynkyn de Worde in 1495.

due to the artist, who ever more tended to see for himself and to reject the older ecclesiastical conventions. It is noteworthy that Leonardo da Vinci's note-books show an attitude to science a century ahead of that of his contemporaries. Mediæval zoology remained very sketchy until the sixteenth century. Fig. 11 shows illustrations of various beasts as they were conceived at the end of the fifteenth century. The elephant may be contrasted with that in Fig. 29, drawn about a hundred years later.

To sum up, we must regard the progress made in scientific knowledge during the period 1100–1400 as trifling considered from the point of view of the world-history of science, for in fact little more was done than to acquire some of the knowledge of the Greeks and Arabs. Yet this, viewed from the standpoint of intellectual achievement, was no small feat.

MEDIÆVAL MATHEMATICS, PHYSICS AND ASTRONOMY

A few important discoveries are claimed by this period. One great mathematician, Leonardo of Pisa (also called Fibonacci), lived in this age. In 1202 he published his great work, the *Liber Abaci* or *Book of the Counting Board*. He was a merchant and had travelled widely and studied the methods of computing used in different parts of the world. Arithmetic was not commonly performed by written calculations until the sixteenth century. The usual system was the use of the *abacus*, an arrangement of beads strung on wires, or counters set out on lines ruled upon a table. Such a ruled table, seen in Fig. 12, was called a "counter", a name which has survived long after the abacus has become obsolete. Fibonacci introduced

FIG. 12
Mediæval Arithmetic. From the anonymous *Rechenbuechlein*. (Frankfurt. 1546.)

the Arabic notation for arithmetic and the positional use of the zero. The new system but slowly displaced the old. In geometry and algebra he equalled and even slightly surpassed his Greek and Arabic masters. But during the two centuries after Leonardo of Pisa we find no further progress other than a slow improvement in the mechanism of calculation and the notation of algebra. Roger Bacon realised to the full the importance of mathematics to the sciences, but here, as in most of his writings, he was better at precept than practice. Various minor contributions were made, but the state of mathematics in Europe in 1490 was not substantially better than it had been in Islam five hundred years before.

Physics fared even worse. The Arabs had carried optics to a high level and Alhazen (*c.* A.D. 1000) had studied reflection from plane, spherical, cylindrical and parabolic mirrors. His treatise was translated in 1278. Roger Bacon wrote with great enthusiasm on optics. His mind, as ever, dwelt on the possibilities of optics rather than its practical study. His assertion that *it was possible* to

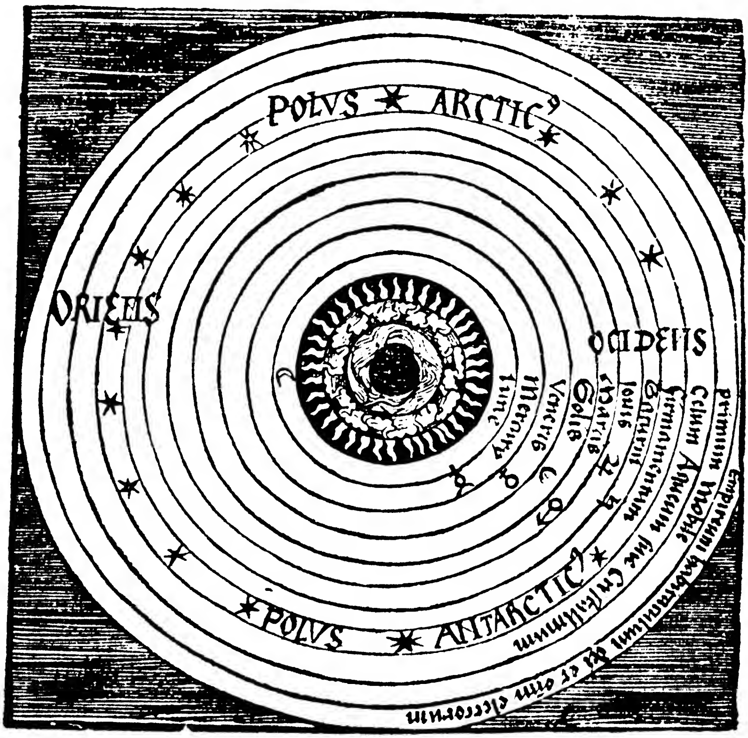


FIG. 13

A diagram of the mediæval conception of the universe. The central earth is surrounded by successive spheres of water, air, and fire. Beyond these, successively, are the spheres of the Moon, Mercury, Venus, the Sun, Mars, Jupiter, Saturn, the firmament of fixed stars, the crystalline sphere, the Primum Mobile (which moved the whole), and the Empyrean, which was the habitation of God and his elect. (From *Margarita Philosophica*. Reisch. 1508.)

make a device by which small writing could be read at a very great distance has suggested that he was acquainted with the telescope; this is not, however, the case. Bacon none the less understood in a general way the reasons for the magnification of a simple lens, and it seems that the knowledge of lenses, which dates back to classical times, became generally diffused about 1250–60. Its first application was in the making of spectacles. These are referred to as early as 1280, though they remained costly until the sixteenth century.

Mechanical invention amounted to little before 1400. The invention of the weight-driven clock seems to belong to this period, though, until the discovery of the pendulum as a means of regulating it, it remained a very inaccurate instrument and needed daily regulation.

Astronomy made but negligible advances in these years; the theory of Aristotle, based on concentric spheres carrying the heavenly bodies and encircling a spherical earth, was the official belief. This theory could not accurately explain the planetary motions which had been very well worked out by the Greeks and Arabs. Ptolemy's theory, in which the planetary spheres were not concentric, and in which smaller spheres rolled between larger ones like the "planet wheel" of a gear-box (Fig. 4), explained the planetary motions with fair accuracy. The earlier mediæval astronomers by no means generally adopted this theory, partly because it did not fit in with their idea of the inherent symmetry of the universe; and partly, perhaps, because it was difficult to understand. Between the time of Ptolemy and that of Copernicus the progress made in astronomy was little more than that of the correction and extension of tables.

The popular view of the universe at this period was

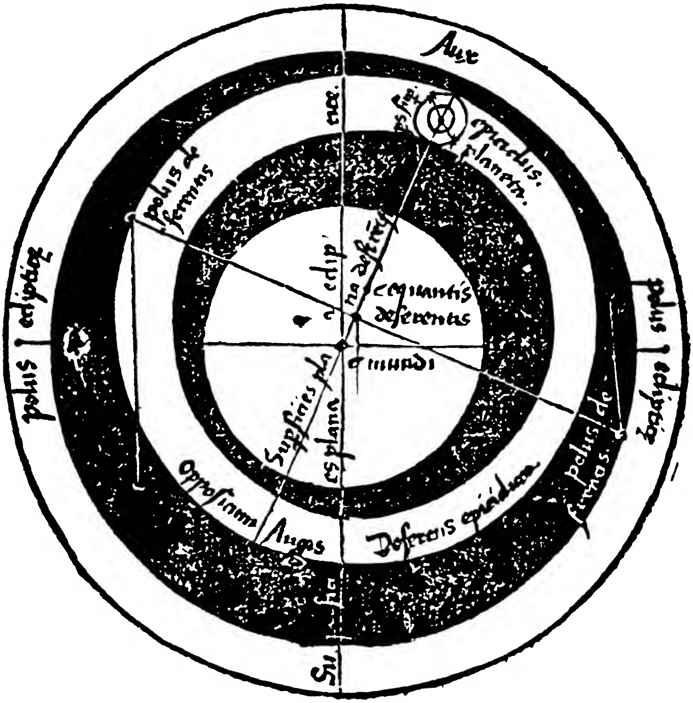


FIG. 14
The orbit of a planet on the Ptolemaic system (*cf.* Fig. 4). (From *Margarita Philosophica.* Reisch. 1508.)

taken largely from Dante's *Divina Commedia*, which derives its system of the universe from St. Thomas Aquinas and ultimately from Aristotle.

MEDIÆVAL MEDICINE

The progress of medicine throughout the Middle Ages was slow. By the year 1250 the medical knowledge of the Arabs—chiefly derived from the Greeks—was largely absorbed. But beyond this little advance was made. In Italy and France the technique of surgery was slowly

developed by such men as Guy de Chauliac (*c.* 1360); but the authority of Galen, Aristotle and Avicenna was so much esteemed that physicians and anatomists hesitated to believe their senses if they observed any fact which conflicted with the works of these masters.

Dissection of the human body was resumed by Mondino about 1315 and became a fairly common procedure in the succeeding century. Dissection, which was carried out in a rather perfunctory manner, led, however, to very little progress, because the object of the mediæval anatomists was to demonstrate to students the correctness of Galen's works on anatomy, and not to discover anything new.

As in previous ages, physical medicine and surgery co-existed with a spiritual or magical medicine. The use of charms and amulets was extensive. The attitude of the Church towards magic was undecided. Anything suggesting a pagan nature-worship was condemned, but the notion of occult virtues contained in herbs and gems was not thought to be inconsistent with the view that all things were marvellous works of God. The belief in demons was universal. Theologians generally allowed that they had power; the invocation of them by magical means was regarded as effective but sinful. Whether theologians condemned the idea or no, magical practices for cure of diseases of man and cattle and for securing other desirable ends flourished exceedingly.

The central theory of popular mediæval science, the influence of the Macrocosm on the Microcosm, involved a belief in astrology; and this age-old theory was the one aspect of science which was important in the world-view of the time. The earth lay at the centre of the universe, around it rotated the planetary spheres. All things within

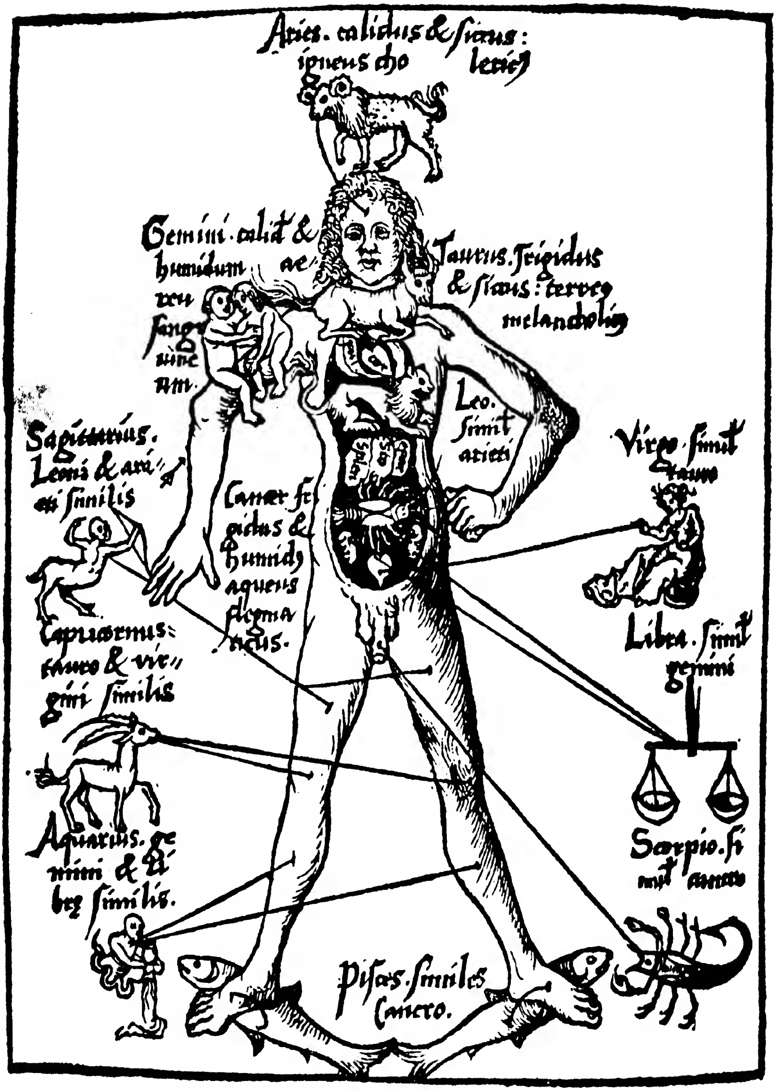


FIG. 15

The correspondence between the parts of the body and the signs of the Zodiac. (*Margarita Philosophica.* Reisch. 1508.)

the moon's sphere were grouped as The Inferiors; the heavenly bodies were classed as The Superiors. The Superiors were thought to be animate intelligences or perhaps links in the causal chain stretching from God to Man. From them proceeded influences of intense potency which connected every gem, herb, animal or man—every object, in fact, animate or inanimate—with the planets, sun, moon and stars. The journeys of the planets, moon and sun through the signs of the zodiac influenced everything on earth: astrology was therefore the most important of practical sciences. Each part of the human body was under the influence of a particular sign of the zodiac (Fig. 15); hence the state of the heavens was of the utmost importance to the physician, and even so rational a philosopher as Roger Bacon declaims against the physicians' supposed neglect of the science of astrology. Much importance was attached to suitable choice of days on which to let blood; and the course of a disease was commonly predicted by studying the planetary aspects for the day when the patient fell sick. Chaucer's description of his Doctour of Phisik shows us the ideal physician of the fourteenth century.

> With us ther was a doctour of phisik;
> In all this world ne was ther noon hym lik,
> To speke of phisik and of surgerye;
> For he was grounded in astronomye.
> He kepte his pacient a full greet deel
> In houres, by his magyk natureel.
> Wel koude he fortunen the ascendent
> Of his ymages for his pacient.
> He knew the cause of everich maladye,
> Were it of hoot, or cold, or moyste, or drye,

And where they engendred and of what humour;
He was a verray parfit praktisour.
The cause y-knowe and of his harm the roote,
Anon he gaf the sike man his boote.
Ful redy hadde he his apothecaries
To sende him drogges and his letuaries,
For ech of hem made oother for to wynne,
Hir frendshipe nas nat newe to bigynne.
Wel knew he the olde Esculapius
And Deyscorides, and eek Rufus
Old Ypocras,[1] Haly and Galyen,
Serapion, Razis and Avycen,
Avverrois, Damascien and Constantyn,
Bernard and Gatesden and Gilbertyn.
Of his diete mesurable was he,
For it was of no superfluitee,
But of greet norissyng and digestible.
His studie was but litel on the Bible.
In sangwyn and in pers he cladd was al,
Lyned with taffata and with sendal.
And yet he was but esy of dispence,
He kepte that he wan in Pestilence.
For gold in phisik is a cordial,
Therfore he lōvede gold in special.

MEDIÆVAL CHEMISTRY

The department of natural knowledge to which, after Medicine, the most practical attention was given in the Middle Ages was Chemistry, which formed a part of the mysterious Art of Alchemy. Before about A.D. 1150

[1] Hippocrates.

Alchemy was not known in Western Europe and the Chemistry of the time consisted in the preparation of drugs and in various technical arts such as the making of pigments and dyes. At a date near A.D. 1150 one most important pharmaceutical discovery was made—that of alcohol. Distillation apparatus had been in use since A.D. 250 or earlier; wine was not only an article of daily use, but also greatly employed in chemical and pharmaceutical operations; yet it is only in 1167 that we find reference to the making of alcohol by distillation of wine. It seems possible that even the strongest distillate which the early stills would separate from wine contained so much water that it would not burn. The secret of success was the addition of salt of tartar and salt, which absorbed some of the water and made the rest less ready to distil. The term alcohol, despite its Arabic sound, was not applied to spirit of wine before the sixteenth century: its original Arabic meaning was *a very fine powder,* and notably eye-black. The introduction of gunpowder belongs to the twelfth or thirteenth century. It is first mentioned, it would seem, in the works of Roger Bacon (*c.* 1214–1292), though the Chinese knew of it at an earlier date.

The knowledge of Alchemy reached Western Europe about A.D. 1200. The majority of the works on Alchemy of this period give extremely little chemical information, and it is easier to read them as philosophical discussions than as practical chemistry. Alchemy was always regarded as a secret tradition and, accordingly, the information which its texts contain is deliberately concealed and is presented under the cover of a largely inexplicable symbolism. Moreover, throughout the long history of Alchemy, there have always been those who treated the Art as a system of human regeneration and those who

treated it as a practical chemical process designed to accomplish the regeneration of the base metals into silver and gold; nor is it easy to distinguish whether one or both of these interpretations are to be given to any particular text.

In the thirteenth century alchemy was both practised and discussed by the learned men of the time, most of whom were monks; in the fourteenth and fifteenth centuries it attained very great popularity among all classes—so much so that Canon Ripley (1415–1490) and Thomas Norton (*c.* 1477) lament the fact that it is practised by all and sundry, even by brewers, tinkers and the like.

Thus Thomas Norton tells us:—

"Of every estate that is within Mankind
If yee make search much people ye may finde,
Which to *Alkimy* their Corage doe address
Only for appetite of Lucre and Riches.
As *Popes* with *Cardinalls* of *Dignity*,
Archbyshopes with *Byshopes* of *high* degree;
With *Abbots* and *Priors* of Religion,
With *Friars*, *Heremites*, and *Preests* manie one,
And *Kings* with *Princes* and *Lords* great of blood,
For every estate *desireth* after good;
And *Merchaunts* also which dwell in the fiere
Of brenning Covertise, have thereto desire;
And *Common workemen* will not be out-lafte,
For as well as *Lords* they love this noble Crafte!
As *Gouldsmithes* whome we shulde lest repreve
For *sights* in their Crafte meveth them to beleeve:
But wonder it is that *Wevers* deale with such warks,
Free *Masons* and *Tanners* with poore *Parish Clerks*;
Tailors and *Glasiers* woll not thereof cease,

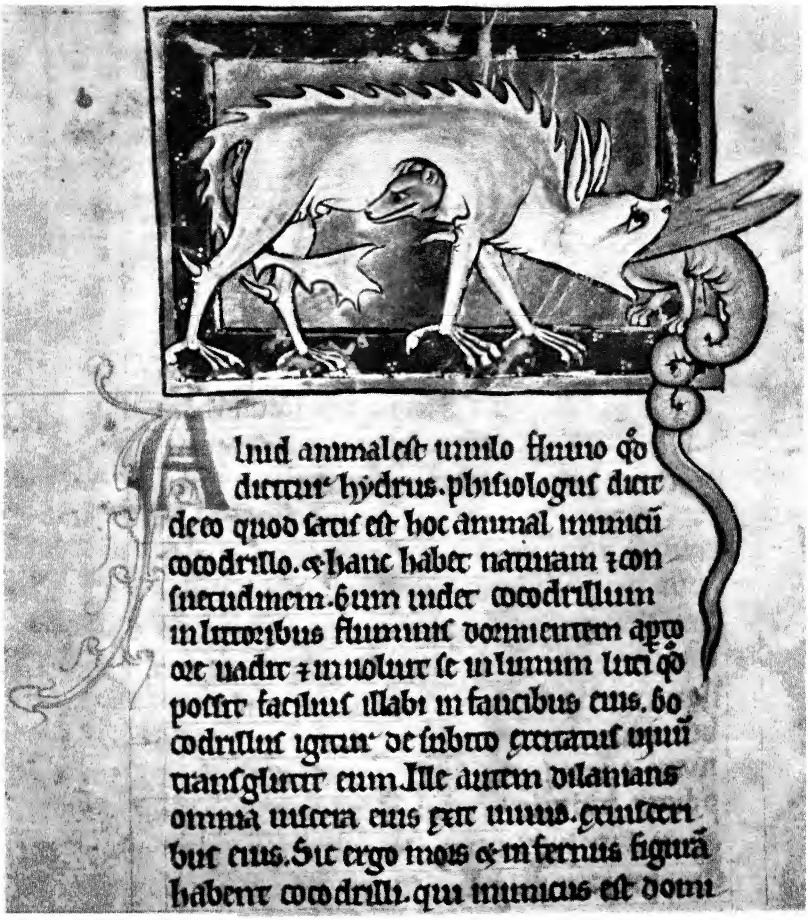


PLATE IV

Natural history about 1170 A.D. The miniature illustrates the crocodile and the hydrus or water-serpent, a dweller in the Nile. The hydrus lay in wait and contrived to be swallowed by the crocodile. It then devoured the crocodile's vitals and escaped. The crocodile is taken as a symbol of Hell and the hydrus of our Lord. (British Museum. Royal MS. 12. C. xix. f. 12. v.)

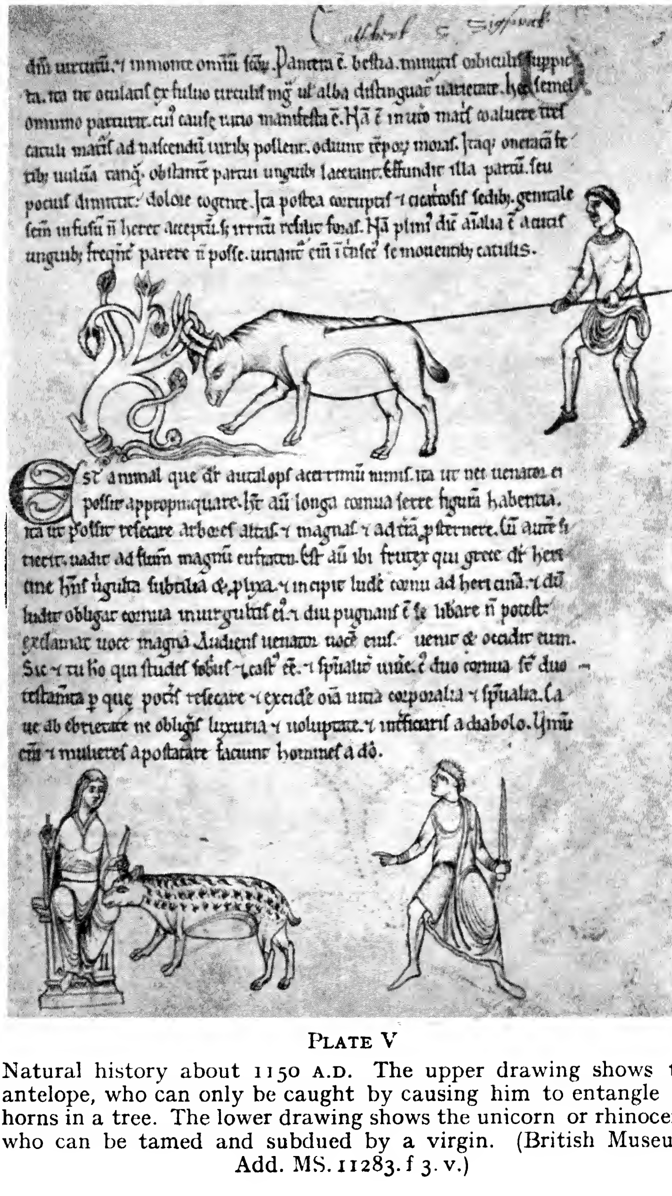


PLATE V

Natural history about 1150 A.D. The upper drawing shows the antelope, who can only be caught by causing him to entangle his horns in a tree. The lower drawing shows the unicorn or rhinoceros who can be tamed and subdued by a virgin. (British Museum, Add. MS. 11283. f 3. v.)

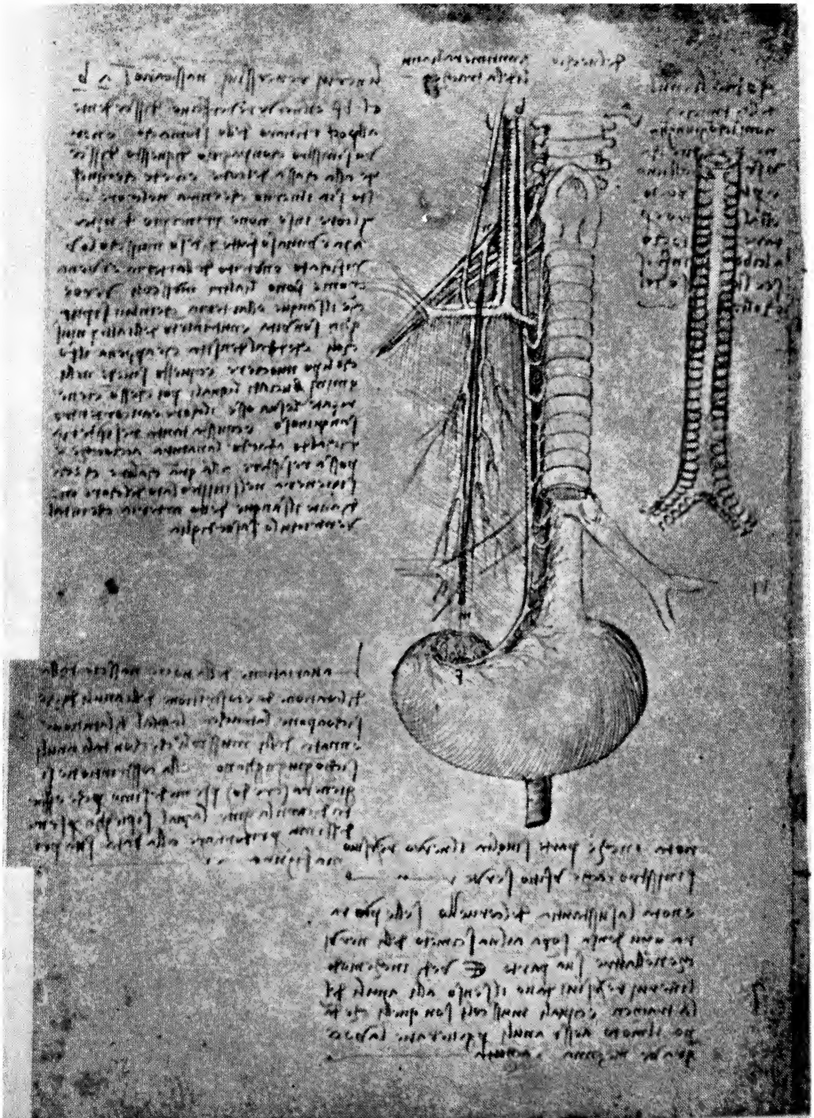


Plate VI

A page of Leonardo da Vinci's notebooks, showing the stomach, windpipe and other organs.

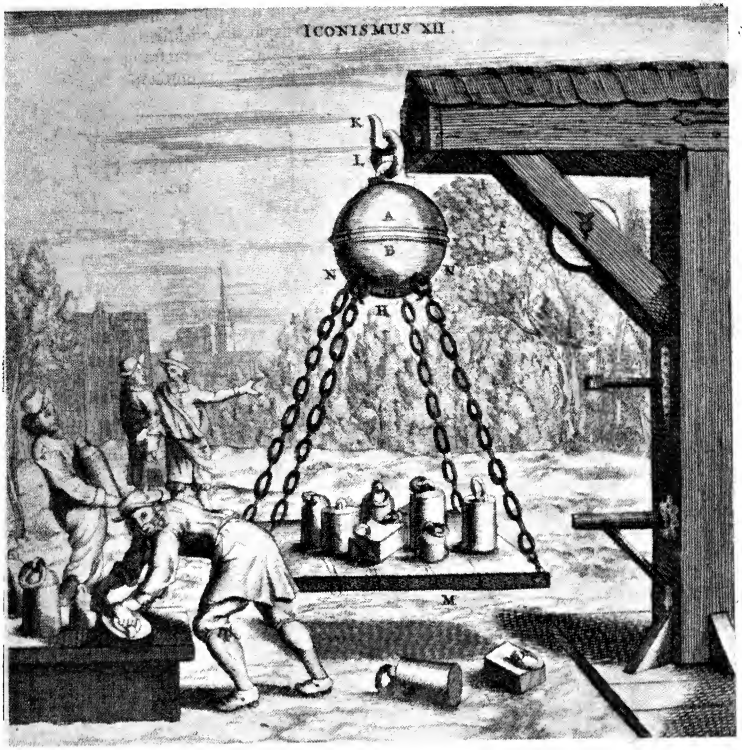


PLATE VII

Measurement of the force needed to separate two evacuated hemispheres. (From Otto von Guericke's *Experimenta Nova.* 1672.)

And eke Sely *Tinkers* will put them in the prease
With greate presumption; but yet some collour
there was
For all such Men as give Tincture to Glasse:
But many *Artificers* have byn over-swifte
With hasty Credence to fume away their thrifte:
And albeit that losses made them to smarte,
Yet ever in hope continued their hearte,
Trusting some tyme to speede right well,
Of many such truly I can tell,
Which in such hope continued all their lyfe,
Whereby they were pore and made to unthrife:
It had byne good for them to have left off
In season, for noughte they founde but a scoffe,
For trewly he that is not a great *Clerke*
Is nice and lewde[1] to medle with this warke;
Ye may trust me well it is no small inginn
To know all secreats pertaining to the Myne."

This widespread practice of Alchemy must have led to a general understanding of chemical laboratory operations, though the discoveries made were but few, probably because the attention of the writers was centred on but one matter, the making of gold. None the less, we must record one most important piece of work, recorded in the writing of Geber, namely the discovery of the mineral acids, sulphuric acid, nitric acid and hydrochloric acid—in an impure state, it is true, and imperfectly distinguished from each other. "Geber" was long thought to be the eighth-century Arabic alchemist Jabir, but it would seem that the Latin works which go under the name of Geber are not earlier than 1200 and it is at least doubtful if they

[1] Ignorant.

have Arabic originals. Geber, whoever he was, describes chemical operations very clearly and practically, and deserves honour as one of the few mediæval writers who soiled his hands in a laboratory.

Chaucer was undoubtedly a dabbler in science: he left an unfinished treatise on the Astrolabe, and one of his *Canterbury Tales,* that of the Canon's Yeoman, shows undoubted first-hand acquaintance with Alchemy. It shows us the travelling alchemist labouring unsuccessfully at the Art, while resorting to faked demonstrations of transmutation to gain a living, and it gives a vivid picture of the less reputable side of Alchemy. With his characteristic scepticism Chaucer exposes the weakness of the alchemical instructions for making gold:—

> "Also ther was a disciple of Plato[1]
> That on a tyme seyde his maister to,
> As his book *Senior* wol bere witnesse,
> And this was his demande, in soothfastnesse,
> 'Telle me the name of the privee stoon.'
> And Plato answerde unto hym anoon,
> 'Take the stoon that *Titanos* men name'—
> 'Which is that?' quod he. '*Magnasia* is the same,'
> Seyde Plato. 'Ye, sire, and is it thus?
> This is *ignotum per ignocius.*
> What is Magnasia, good sire, I yow preye?'
> 'It is a water that is maad, I seye,
> Of elementes foure,' quod Plato.
> 'Telle me the roote, good sire,' quod he tho,
> 'Of that water, if it be youre wille.'
> 'Nay, nay,' quod Plato, 'certein that I nylle;

[1] Certain alchemical works composed in the Middle Ages were attributed to Aristotle and Plato.

The philosophres sworn were everychoon
That they sholde discovere it unto noon,
Ne in no book it write in no manere,
For unto Crist it is so lief and deere,
That he wol nat that it discovered bee,
But where it liketh to his deitee
Man for tenspire, and eek for to deffende
Whom that hym liketh; lo, this is the ende."

The alchemical writers between A.D. 1200 and 1500

FIG. 16

Manufacture of acid for the refining of gold. (Agricola. *De Re Metallica.* 1553.) Note the resemblance to the apparatus of Figs. 9 and 23, in use 1200 years earlier and 200 years later.

were very numerous, but their recorded contribution to pure science was of the smallest. The development of the practical technique of chemistry must however have been greatly furthered by the popularity of alchemical experiments. Another source of chemical progress was the great increase in the mining of metals, which took place in the fifteenth and sixteenth century. Mineral acids and various salts were required in large quantities for the refining of metals and we find, about 1500, the beginnings of chemical manufacture. Fig. 16 shows an illustration of an early sixteenth-century laboratory in which acids are being made on a large scale. The use of chemicals in the arts naturally led to a greater interest in their properties during the sixteenth century, but it was the seventeenth century that saw the foundation of the science of Chemistry.

CHAPTER V

SCIENCE IN THE RENAISSANCE

SCIENCE AND THE RENAISSANCE

THE years between 1450 and 1650 saw the gradual destruction of the primitive and unreal mediæval outlook on nature and the gradual evolution of the spirit of modern science. Since the seventh century A.D. the mediæval conception of the Cosmos had been steadily elaborated and defined. The material universe was small, transient and evil: it was controlled by influences emanating more or less directly from the Deity. The established religion was thought to have the ability to decide, on the authority of the Fathers of the Church and of Holy Writ, all questions, whether of theology, morality, or scientific fact. The universe was a hierarchy in which the layman had no high place.

In the twelfth and thirteenth centuries this system could still satisfy the world's needs, though, even then, the preservation of settled doctrine could only be attained by constant repression of heresy.

The destruction of the scholastic scheme of the world may be traced back to the natural light-heartedness of man affirming his delight in this world which the Church had pronounced to be despicable and as nothing beside the glories of the next. A twelfth or thirteenth century poem expresses the conflict:—

Vita mundi, res morbosa,
Magis fragilis quam rosa,
Cum sis tota lacrymosa,
Cur es mihi graciosa?

which may be translated:—

Worldly life, by sickness rent,
Than a rose more swift to break,
Why, when I should thee lament,
Does delight in me awake?

This spontaneous feeling for beauty had to express itself. Religious painting, architecture, and poetry, great as they were, could not satisfy it. Soon there developed a secular Latin poetry, then in all countries poetical tales and romances in the vernacular. The stream of non-theological mental activity swelled to a flood.

The first steps towards the founding of a new culture in which this joy of life could find expression were taken in Italy during the fourteenth century. The Papacy and the Mediterranean trade had brought great wealth, and from it had sprung a cultured and leisured society. The learned men of the time found in the classics a new world which was outside the small theological universe, and in which they felt themselves to be free men.

In the fifteenth century the cult of the classics became a ruling passion. The merchant princes and the rulers of Italy vied with each other in collecting Greek manuscripts, most of which they obtained from Constantinople where the Greek learning was still preserved. The spirit abroad was that of humanism—Man's vision of himself as a free being, no longer a slave to his fears and hopes of Hell and

Heaven. The spread of the new spirit was aided by several events. The fall of Constantinople in 1453 helped to diffuse Greek learning which had been hidden there: at the same time there was a weakening of the forces which might have opposed the new learning. Thus the political power of the Holy Roman Empire became diminished, and the Roman Church, which might have been expected to combat the new spirit, actually encouraged it. The intellectual attitude of such popes as Alexander VI and Leo X was that of the humanistic scholar rather that of the man of religion; under their leadership abuses grew up which further enfeebled the Church's power. The limitations of the small world of the Middle Ages were made still more apparent by the voyages to the Indies and later to the New World. Moreover the stream of wealth from these new sources went far to create a powerful merchant-class whose members had leisure and education. From this new source sprung a host of learned laymen, and for the first time since the decline of pagan philosophy learning ceased to be a clerical monopoly.

In the second half of the fifteenth century printing began, and the rate of diffusion of the new classical learning was still further increased.

The Renaissance, which by 1450 was well under way in Italy, soon spread to the wealthy German towns, then to France and the Netherlands. England received its awakening last of all and remained substantially mediæval in spirit until the second quarter of the sixteenth century.

The result of this process was to transform the entire culture of Europe. The changes which came about in science were, however, far less conspicuous than those in other fields. The works of Aristotle and the Arab commentaries thereon remained the standard university

text-books of science until the middle of the seventeenth century. However, the scholastic way of thinking about nature gradually fell into contempt, but the classical learning which took its place, though better in spirit, was but a dim lamp to most departments of science. The re-discovery of Greek literature did not reveal much that was new: far more important was the discovery by the scholars and scientists of the sixteenth century that in classical Greece, almost two thousand years before, freedom of thought had reigned. But freedom of thought alone was not enough to build a science; the idea and practice of the experimental method had to be established before rapid progress could begin.

The Renaissance was followed by the Reformation. In the early sixteenth century the various Protestant Churches broke away from Rome. The power of the Papacy had been greatly enfeebled by abuses within and wars from without, and until the middle of the century she made little resistance to heresies which in earlier times would have been swiftly eradicated by fire. But after the Council of Trent (1545–1563), she inaugurated the Counter-Reformation. In Italy and Spain the new doctrines, whether scientific or religious, were opposed by the Inquisition. The activity of the heresy-hunters was, however, chiefly directed to the teachers of false doctrine. It cannot be said that anyone actually suffered death for his scientific opinions alone. Giordano Bruno was condemned chiefly on account of his theological opinions: Galileo received the mildest of punishments, but, had he not recanted, prison or the stake might well have been his lot. The Protestant countries were little more enlightened, but, save in Geneva, where Calvinism reigned, they were rather more tolerant. Calvin regarded

the repression of false doctrine as vitally important. In 1553 at Geneva the physician Servetus was burnt for his theological opinions: but it is notable that one of the charges brought against him was concerned with a matter of scientific fact, namely, that he had declared Judæa to be a wretched barren country, which opinion "inculpated Moses and grievously outraged the Holy Ghost."

THE ESTABLISHMENT OF THE COPERNICAN THEORY

No advance in science has influenced the world-view of Man more widely than the discovery that the earth was not the centre of the universe. The discovery was due in the main to the German school of astronomers, though its chief popular expositor was an Italian, Galileo.

Johann Mueller, ordinarily known as Regiomontanus, lived from 1436 to 1476, and studied under George Purbach at Vienna. He realised that the current Latin versions of Ptolemy's *Almagest* were full of errors, which is not surprising, inasmuch as they were translated from Arabic translations of the original Greek. Accordingly he translated Ptolemy's work direct from the Greek version and also wrote a commentary on it. He made great advances in trigonometry and calculated very accurate tables of sines and tangents of angles. He set up an observatory at Nürnberg, in co-operation with Bernard Walther, and equipped it with instruments, including for the first time weight-driven clocks: the telescope was, of course, as yet unknown.

The work of calculating accurate trigonometrical tables was carried on by George Joachim (usually known as Rheticus). The effect of the work of these two astrono-

mers was to put the world in possession of a clear view of the ancient astronomy and the means of making accurate astronomical calculations.

The ancients had not all believed that the earth was immobile; for the Pythagoreans believed rather that a central fire, invisible from the earth, was the centre of the universe and that the earth revolved round it. Aristarchus of Samos had developed quite an adequate heliocentric astronomy. Nicolaus of Cusa in 1440 stated quite clearly, on philosophic grounds, that the earth could not be the centre of the universe. No exception was taken to this statement, and he was raised to the rank of Cardinal. In Italy at the end of the fifteenth and beginning of the sixteenth century—a period of toleration—these ideas were freely discussed and were finally given a scientific basis by Nicolaus Koppernigk (Copernicus). Copernicus was born at Thorn, in Prussian Poland, in 1473, and in 1496 studied astronomy at Bologna, where no doubt he met with the idea that the earth might not be the centre of the universe but might merely be a planet revolving round the sun. He later became a Canon of Frauenburg in East Prussia and from 1513 made a study of these views. His task for some years was to show that the mass of astronomical observations then available was completely in accord with such a theory.

Copernicus was cautious about announcing his results. He sounded the opinion of the Pope and although the Church's view was favourable he would not publish his great work *On the Revolution of the Heavenly Bodies* until Rheticus over-persuaded him. The first copy of the book reached Copernicus on his death-bed in 1543. A preface, inserted by a friend, solemnly assured the world that the book was purely hypothetical, and this may have delayed

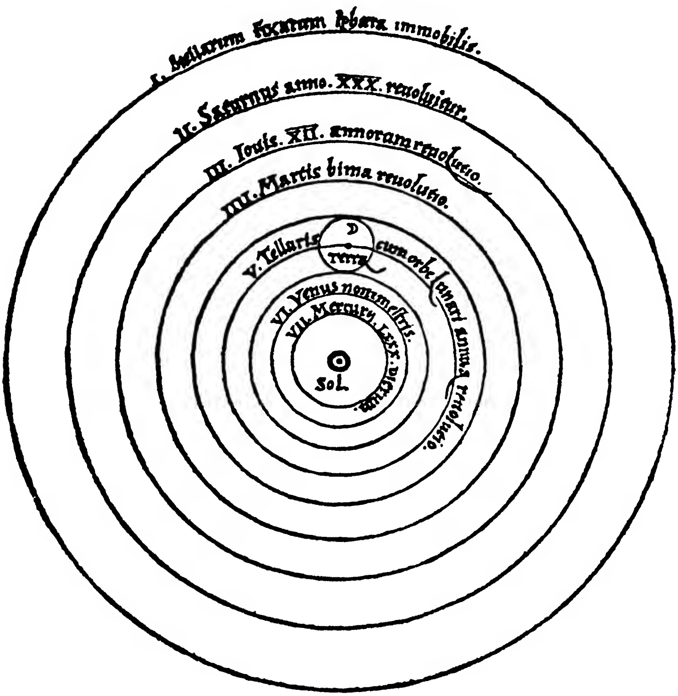


FIG. 17
Copernicus' picture of the sun and planets. (From *De revolutione orbium celestium.* 1543.)

the storm of controversy which was later to arise. The attitude of the Church in the sixteenth century was that the heliocentric theory might be put forward as a hypothesis, but not asserted as a fact.

During the next fifty years no appreciable progress was made. Late in the sixteenth century Giordano Bruno (1548–1600) constructed a philosophy in which the Copernican system was asserted as an essential doctrine. He was forced to leave Italy, but continued to write, not only attacking the traditional scientific beliefs, but also the mysteries of religion. It was to be expected that, at this date, when the Counter-Reformation was at its

height, the full power of the Catholic Church should be exerted against such a man. In 1593 Bruno was imprudent enough to return to Italy and in 1600 was burned as a heretic.

Astronomy meanwhile made rapid progress in the hands of Tycho Brahe. Tycho Brahe (1546–1601) was essentially an observational astronomer. He did not accept the Copernican system in its entirety, but adopted a system of his own which was a compromise. It must not be forgotten that the Copernican system was not perfect. It assumed the planetary orbits to be circles, whereas they are in fact ellipses, and so could not give a perfect explanation of the observed facts. Moreover, it seemed to Brahe that if the earth were revolving in an orbit, the stars should show a parallax, a shift in position when seen from opposite sides of the earth's orbit. He would not credit the idea that the stars were so hugely distant that the shift, though existent, was too small to be detected by his instruments.

The standard of astronomical accuracy was still low. Many attempts were made to measure the distance of the *nova* of 1572, mentioned below, and results varying from a few hundred miles to an infinite distance were obtained. Tycho Brahe's great work was the setting of a new standard of accuracy. He constructed very large and reliable astronomical instruments by which the changing positions of the heavenly bodies could be far more accurately mapped than ever before. He thus provided material for Kepler's great discovery of the laws of planetary motions.

Two of Brahe's discoveries are of particular note. He measured the parallax of a comet and so proved that it was much more distant from the earth than was the moon. Up to this date it had been believed that comets were

mere appearances or exhalations of the earth's atmosphere: Brahe showed that they were heavenly bodies, a discovery which created further difficulties for the Ptolemaic system, which provided no explanation of how the comets could move among the planetary spheres. In 1572 a *nova* or new star appeared in the constellation Cassiopeia. It had been a doctrine of philosophy that the stars and all heavenly bodies above the sphere of the moon were perfectly immutable. Was this new star a mere atmospheric appearance? Tycho tried to measure its parallax, but could detect none, and so concluded that it must be a true star and that therefore the stars were subject to change. Another brilliant *nova* appeared in 1604 and aroused further controversy and the question whether these *novae* were true stars was still in dispute in 1632 when Galileo's *Dialogues* were published.

Nine years after Tycho Brahe's death, astronomy was transformed by the discovery of the telescope, which brought with it the realisation that the heavenly bodies were not merely lights but worlds. Astronomy herein depended, as so often since, on the development of the science of Physics.

Lenses had been known since antiquity and had been well studied by Alhazen (*c.* A.D. 1000), Roger Bacon and others. In the sixteenth century they became more familiar as spectacles came into common use. In 1608 a spectacle-maker's assistant hit on a combination of lenses which made a simple telescope. The report of the invention reached Galileo de Galilei, already a great physicist (p. 141); he considered the possibilities and in 1609 constructed such an instrument and directed it to the skies. As he constructed better and better instruments his discoveries extended. First he saw the craters of the moon,

and realised it was not smooth and spherical, but rugged like the earth: further improvements in his instruments enabled him to see the Milky Way as a cloud of stars, and the planets as tiny discs; finally he detected the satellites of Jupiter. These, as they revolved round the great planet, gave a visible demonstration that smaller bodies might revolve about larger bodies which were not the centre of the universe, and seemed to afford a demonstration of the Copernican system.

Since remote antiquity man had known seven planets or "wanderers in the heavens" and no more. These satellites by their motion clearly qualified as planets. This disturbance of the fitness of things roused furious protests. Some even refused to look through the telescope lest they should be forced to see and believe. Later Galileo studied sunspots, an almost more disturbing assault on the tradition of heavenly perfection. Tremendous interest was aroused. This new Astronomy was no longer a matter of learned treatises: it was the talk of all the educated population of Europe. In 1613 the Church began to take notice of Galileo's theories: sides were taken even in theological circles. His ideas were denounced to the Inquisition, which rather reluctantly turned its attention to him, and in 1616 the propositions that the sun was the centre of the world and immovable, and that the earth was not the centre of the world and was not immovable, were declared by the Holy Office to be false, philosophically absurd and also heretical. Accordingly, Galileo was admonished to abandon his opinions but was not obliged formally to recant his beliefs. Urban VIII, who became Pope in 1623, had disapproved of the Inquisition's action and was at first very favourable to Galileo's work. Encouraged by this august support Galileo continued his

astronomical work and in 1632 published his famous *Dialogues* dealing with the rival Ptolemaic and Copernican systems. Unfortunately, the Pope was persuaded by Galileo's enemies that the book transgressed the order of 1616: possibly the Pope also believed that he was personally held up to ridicule. Hitherto he had been favourable to Galileo, but now withdrew his protection; the book was condemned by a commission and the great astronomer at the age of sixty-nine appeared before the Inquisition.

He recanted his opinion and abjured the Copernican system. The Inquisition treated him much more mildly than was usual, and although the rest of his life was spent in strict seclusion as a prisoner in his own villa, he was allowed to continue his work. His works were placed on the *Index Expurgatorius*. Not until 1835 were they removed from this list of works prohibited to good Catholics, although the prohibition was in fact ignored after a few years. It is interesting to note that Kepler (p. 185) was condemned in 1596 by the Protestant Theological Faculty of Tübingen for asserting exactly the same doctrines as those for which Galileo was condemned. Although he was a Protestant he took refuge with the Jesuits, who honoured his astronomical work. Later he was made Court Astronomer to Rudolph of Prague and so enjoyed adequate protection. Copernican astronomy was unsafe in the latter part of the sixteenth century wherever ecclesiastics, Catholic or Protestant, possessed secular power. In the early seventeenth century the attitude in Protestant countries became more tolerant, and by the middle of that century the heliocentric system was generally accepted as a fact of science, though for many years the literary world continued to think in terms

of planetary spheres. Gradually, however, the work of Kepler, Huygens and Newton filtered through to the public and the heliocentric system became transformed from a scientific theory to a world-outlook.

LEONARDO DA VINCI

The astonishing works of the artist and scientific genius Leonardo da Vinci (1452–1519) stand outside the stream of scientific progress, for they remained as manuscript notes until centuries had passed. His note-books reveal such a man as the world's history cannot parallel; artist, philosopher, and man of science; lofty in thought, daring in speculation, and brilliant in execution. His *Notebooks* show us a man who took all knowledge and art as his province, who used his artist's eye on the world which the scholar sought in his books. As an engineer and physicist we find him carrying out practical hydraulic projects, schemes for canals and irrigation works, designing mills and sluices, inventing the camera obscura, using the expansion of steam to project a cannon-ball. He observed the flight of birds and went far towards the solving of the problem of aviation, for he seems to have made little helicopter models that would rise, and a bigger machine of the movable-wing type. He throws out casually such statements as "The sun does not move" and "A weight seeks to fall by the most direct path to the earth's centre." Most significant of all, he is one of the first to lay down that scientific work must *start* by experiments and *end* with conclusions.

His work as anatomist shows a huge advance; no one before his time did so much dissection. There is evidence

that he dissected thirty or more human bodies, and this despite the opposition of the Church. As significant as his persistence in dissection, was his careful preparation of accurate drawings from the object before him. He interpreted the results of his dissections with extraordinary penetration—almost attaining to a knowledge of the circulation of the blood. But none of this knowledge was handed on to his successors. His note-books, which were, oddly enough, written backwards and partly in cipher, remained largely unpublished. A few portions concerned with painting were published in 1651, and the remainder was not described until the nineteenth century.

Leonardo observed fossils and decided they could not be accounted for as relics of the Deluge, nor, as others believed, as products of the creative influence of the stars. He doubted the story of the Flood, but his doubts of Biblical stories did not lead him to disbelief, but only to an attempt to reconcile them with his observations.

PARACELSUS

An extraordinary link between the world-views of the Middle Ages and of the Renaissance is to be found in Paracelsus (1493–1541), physician, alchemist and mystic. The name Paracelsus was assumed by him, his real name being Theophrastus Bombast von Hohenheim. Paracelsus was among those who attacked the science and philosophy of Aristotle and the Arabs. Arrogant, boastful, vituperative and obscure in language, he attracted widespread attention. At his first public lecture he publicly burned the works of Avicenna and Galen in a brass pan with sulphur and proclaimed himself far superior to the great

physicians of antiquity. But the new medical theory he sought to erect was so strange a medley of the supernatural and the physical, set out in such a fantastic garb, that it is to be doubted whether he advanced or retarded medical science. His positive contribution was the simplification of the pharmacopœia and the introduction, or at least popularisation, of opium and of a number of mineral drugs —compounds of mercury, antimony, lead, copper and iron. His theory of the world was fundamentally the ancient one in which the Macrocosm, the great world of nature and the heavens, is in correspondence with the Microcosm, the small world of Man. All things, he believed, had a spirit, and so could influence the spirit of man and be influenced thereby.

Diseases he believed to be due either to external spiritual influence or to the failure of the stomach's directive spirit, "the Archeus", to separate the poisonous part of the food from the valuable part. His theories form no part of modern science. His influence was important in two directions: first in introducing new remedies, good and bad, to the physician's equipment; secondly, as having convinced many of the alchemists that their practical art should be directed towards preparing new drugs from mineral or metallic sources, rather than towards the making of gold, thus giving the chemical worker a simple and attainable object. His influence remained powerful throughout the seventeenth century and even later.

Paracelsus rejected anatomy as a pursuit valueless for the physician, but, while he was yet alive, Fallopius and Vesalius had begun the scientific study of that science and thereby laid the foundation of modern medicine.

CHAPTER VI

THE RISE OF MODERN SCIENCE

THE SCIENTIFIC METHOD

THROUGHOUT the sixteenth century an increasing number of voices were being raised against reliance on authority and in favour of seeing for oneself. Paracelsus, Leonardo da Vinci, Vesalius and William Gilbert all rejected the authority of the ancients and advocated reliance on observation or experiment. The man, however, who first showed the world the scientific method in operation was Galileo. He was not content with decrying the dependence of the science of his time on the works of Aristotle. He consistently *used* the modern scientific method, framing probable hypotheses and putting them to the test of experiment. He devised apparatus, made accurate measurements and treated them mathematically. He may be regarded as the prototype of the man of science. But Galileo afforded the world only an example of Scientific Method; he did not express that method in general terms.

Francis Bacon, Lord Verulam (1561–1626), crystallised the strivings of the age towards scientific method. There has often been a tendency to decry Bacon because he carried out but little experimental work, and indeed he was somewhat lacking in scientific genius.

We must not expect, however, from the same man,

pre-eminence in scientific philosophy and in practical science. As Cowley says of him:—

> But life did never to one Man allow
> Time to Discover Worlds and conquer too;
> The work he did we ought t'admire,
> And were unjust if we should more require
> From his few years, divided 'twixt th' Excess
> Of low Affliction, and high Happiness:
> For who on things remote can fix his sight,
> That's always in a Triumph or a fight?

Bacon's contribution to science was the definition of the errors inherent in the manner in which knowledge had been hitherto obtained. He was profoundly impressed by the partial, uncertain, and useless character of most of men's knowledge. The object of knowledge, he considered, was not to find some abstract metaphysical truth about the nature of things, but to give power over the world. He thus sets up as a lofty object the making of scientific devices for man's practical use.

Archimedes felt that the practical devices which he constructed were unworthy of being recorded, and that only general abstract principles were worthy subjects of philosophy. Bacon reversed this view, and so by his influence made practical science a pursuit acceptable to the greater minds.

Bacon thought that since the world had made so little progress in so many centuries, its method of acquiring knowledge must be faulty. He therefore criticised destructively the accepted attitude to learning. He attacked those who rested on the authority of the classical world, and who believed all knowledge to be comprised

in the works of Aristotle. Even more important, however, was his attack on the speculative philosophers, who starting from preconceived ideas, built up a world-system by abstract reasoning.

Bacon then examined in much detail the various errors to which the human mind is subject. Prominent among these are the tendency to generalise from insufficient evidence, to yield to individual prejudice, and to pay too much respect to words and philosophical systems which may have little meaning or validity.

Bacon's positive proposal was the building up of a system of natural science by his method of induction. The first task of the investigator of a phenomenon was to collect instances of it, to perform as many experiments as possible upon it, and then to gather from these accurately observed facts some general principle which ran through them all. This process is an important part of the scientific method as applied to-day, for an accurate knowledge of facts, gained by experiment, is the foundation of natural science. The weakness of Bacon's method is that until some hypothesis has been reached as to the nature of the phenomenon investigated it is difficult either to devise significant experiments or to understand those that have been made.

The modern scientific investigator proceeds, first, by the Baconian method, establishing a few well-tested facts and setting up from these a rational hypothesis capable of explaining them. The next step is not Baconian; for, having erected his hypothesis, the investigator deduces from it fresh consequences and tests these experimentally. The scientific work of the seventeenth century was not a little hampered by too strict a Baconian procedure. Enormous numbers of experiments were tried, but they were not as a rule devised to settle any crucial point,

and so lacked significance and often slipped into oblivion.

The influence of Bacon was great. The spirit of his work led to a general realisation of the importance of science, the result of which was one of the great events in scientific history, the foundation of the Royal Society.

The formation of scientific societies was one of the chief advances of the seventeenth century. In this period the scientific amateur came to the fore, and perhaps for the first time since that of ancient Greece, science became a general interest of the intelligent. It may be that a century and a half of indecisive religious and political experiment had tired men of these subjects and that natural science at last gave promise of certain and indisputable knowledge. The pursuit of science is difficult for the unaided amateur, unless he is of great wealth; and there naturally arose proposals for societies which should undertake systematic investigations. Bacon in his *New Atlantis* sets out a grandly conceived "Solomon's House", a sort of College or Temple of science; others, such as Cowley the poet, and Evelyn the diarist, made similar suggestions.

The first scientific society was the *Accademia Secretorum Naturae*, founded in Naples in the year 1560. Much more well known is the *Accademia dei Lincei*, formed in Rome in 1600. It came to an end in 1630, chiefly through the death of its President, Prince Cesi. In 1657 the *Accademia del Cimento* was formed in Florence. Its members included Borelli the mathematician, Redi the biologist, and many others. The *Accademia del Cimento* was remarkable for its team-work. Its members as a whole concentrated on particular problems and were very successful in elucidating

them. The results were published in a book which became a standard manual of physics. The weakness of the *Accademia* was its reliance on one magnificent patron—Leopold de Medici. In 1667 he became a cardinal and could no longer support the suspect subject of natural science, and one of the most remarkable of scientific societies came to an end.

In England groups of philosophers began to meet for discussions from about 1645; and in 1659, when the political difficulties of the Commonwealth were subsiding, meetings began to be held at Gresham College in the City of London. After the Restoration, these meetings became more fully organised, and in 1662 Charles II, who must be gratefully remembered for his patronage of science, gave the society a Royal Charter. The Royal Society regarded Bacon as its inspirer and moulded its work on his system; thus, at this period, we find much experimentation and little interpretation. But in utter contrast to the work of earlier times, we find a most critical examination of all the scientific work submitted. A further transformation occurs about the time of Newton: and, as Whewell has said, in the earlier or Baconian period, a group of philosophers began to knock at the door of truth; but Newton was the first to force it open. From the closing years of the seventeenth century we no longer find rather isolated and sometimes almost childish experiments, but increasingly meet with scientific papers informed by theory and tested by experiment.

In France a rather similar state of affairs prevailed. In the earlier part of the century such great men as Fermat, Pascal and Gassendi met privately for discussions: these meetings led in 1666 to the formation of the *Académie des Sciences,* which was a royal foundation with the authority

and financial resources of Louis XIV himself. Its method of work differed from that of the Royal Society in that most of their experimental operations were carried on in the laboratories of the *Académie* rather than in the homes of individual workers.

The German States, despite their later scientific eminence, lagged behind France and England in the seventeenth century. Several small societies were formed, but the Berlin Academy, which was very carefully planned by Leibnitz, did not receive its royal charter until the year 1700.

The importance of the learned societies for the promotion of scientific research was incomparably greater than that of the universities. The teaching of the new science was, however, begun in the last years of the seventeenth century at Oxford, which University was the first to appoint a professor of Chemistry. In Cambridge the influence of Newton was important, but in later years the science taught was almost exclusively mathematical.

One of the most important functions of the learned societies was the foundation of scientific journals. The publication of experimental results in the form of text-books or monographs necessarily put a strain on the resources of the less wealthy men of science and, moreover, tended to delay publication of important results. Journals such as *The Philosophical Transactions* and the *Journal des Sçavans* provided a convenient way of publishing pieces of work smaller than would require the publication of a whole book and, moreover, made available to the scientific public the results of investigations within a short time of their completion.

SCIENCE AND RELIGION, 1600–1850

The memory of the great nineteenth-century controversies which centred round the conflict between science and the dogmas of the Churches may incline us to believe that religion has been on bad terms with science ever since the latter first rejected authority. This is by no means true. The various Protestant Churches during the sixteenth century on the whole opposed the Copernican theory, though they rarely took overt action against its teachers. The Catholic Church took little notice of the theory until 1616, when the heliocentric view of the universe was declared heretical and its public discussion was forbidden. This prohibition was ineffective by the end of the seventeenth century, although it was not completely revoked until 1835. In England and some other countries there was no opposition at all to the new world-view of science; in fact, throughout the seventeenth and eighteenth centuries and even up to the eighteen-thirties, science was generally held to be the handmaid of religion, and the extension and intricacy of the universe it revealed was felt to redound to the glory of God. It was only near the year 1850 that a serious difference between the biblical and the scientific views of creation was generally seen to exist, and only then was direct issue joined.

Attacks upon the Christian religion were made in the seventeenth century and were a commonplace in the eighteenth century. These attacks were based not on the physical impossibility of the biblical account, but on its inconsistencies and even its ethical faults. Science contributed to the state of mind which led to attacks upon the authority of the Church, though its facts were not used

as weapons. Throughout the seventeenth and eighteenth centuries science was steadily unfolding to the world the picture of a universe, ruled by unvarying laws, in which there was left progressively less room for supernatural intervention. From the discovery of natural laws in a few phenomena to the assumption of their governance of the whole universe was not too long a step for the sanguine to take. The consequent relegation of God from the position of immediate Ruler to that of remote First Cause, was in the eyes of the practical man the next thing to His abolition.

The development of science was made by the experimental method. Preconceived ideas were dropped and every stage of the building of any theory had to be the subject of an experimental proof: the theory itself, if it was to be accepted, had to predict results which were verifiable by experiment. The earlier philosophic theories, on the other hand, had been based on what their framers felt to be consistent with the rational character of the Maker of the Universe or with the perfection which must be expected of the work of One who is Himself perfect. Such theories had proved to be of no assistance to the progress of science, while, on the other hand, the experimental method had rapidly caused a large body of reliable knowledge to be built up. Experimental science was the one department of learning from which philosophic, theological and moral entities were strictly excluded: its brilliant success naturally led to a high opinion of its materialistic and rational methods and to an attempt to extend these to the whole Cosmos. The habit of looking for the truth without respect to the seeker's prejudices, hopes, and fears, began to be established.

From the early part of the seventeenth century there arose a series of thinkers who tended to exalt reason above faith and authority. Opposed to these were, first, the orthodox, who found in Church teaching or in the Bible a literally accurate account of the past and a complete guide to the present and future, and secondly the mystics, who, rejecting the literal meaning of the words of the sacred writings, found them to bear a hidden sense. In religion and philosophy these three parties, freethinkers, orthodox, and mystics, are conspicuous: in the world of science, too, we find them in the sixteenth and seventeenth centuries. Here they are represented, respectively, by the main body of scientific workers, who followed the scientific method: by the rapidly diminishing band of followers of Aristotle and the classical science; and by the scientific mystics, Paracelsus, van Helmont and the alchemists, whose works were still being published in the late eighteenth century, and whose belief was in an Order of Nature informed by Deity and an Universal Soul.

The philosophers of the seventeenth and eighteenth centuries established a world-view based on a universe rigidly conforming to natural law. They rejected authority as a ground for accepting any belief, scientific or theological. They did not, as a whole, reject the existence of a Deity, nor attack the foundations of human morality: they laboured, rather, to show that a *Natural Religion* arose from the application of reason to human conduct. Their attitude, in England, at least, was adopted by the theologians, who, while accepting the Christian revelation, based their apologetics upon reason—giving but a secondary place to faith.

While such philosophers as Descartes, Locke, Spinoza and Leibnitz had made it difficult to accept the Christian

revelation on grounds of faith, the work of Bayle, Hume and Voltaire was definitely anti-Christian or even atheistic. They subjected the sacred writings to a critical and hostile scrutiny. They exposed the inconsistencies and moral deficiencies which necessarily were found in the ancient and miscellaneous collection of works which make up the Christian canon. Such treatment, unfair and sterile as it must always prove, was but the natural reaction to the absurd exaltation of these writings to the position of literally inspired books. The weapons of ridicule and satire were brought into play, and the world was made ready for the rejection of Christianity by the French Revolutionaries. An inevitable reaction followed in the early nineteenth century, especially in England.

During the seventeenth and eighteenth centuries, the Dissenters became an ever-increasing force in favour of literal Christian belief. Derived from the Puritan sectaries on the one hand and from mystics like William Law (himself a churchman) on the other, the Dissenters stood for the mystical rather than the rational view of Christianity, and supported the literal interpretation of the Bible. A great part of the trading classes of England became converted to their view. These classes rose to prominence and power in the early nineteenth century: their example, together with the reaction from the hated revolutionary views, made the atmosphere of the early nineteenth century peculiarly pietistic. On the other hand, by this time evidence was accumulating that the Bible was neither historically nor scientifically an accurate account. These divergent views met in a tremendous controversy of which the first rumblings were heard in the eighteen-thirties, though the main battle was not joined until the 'fifties and 'sixties.

The central motive, then, of scientific and philosophic thought from 1500 to 1850 is the triumph of Reason and of the experimental method over Faith and the principle of adherence to authority.

THE FOUNDATION OF MECHANICS

The first department of Physics to make notable progress in the new age of experimental science was Dynamics, which required a comparatively simple type of experiment adapted for interpretation by well-known mathematical methods. Galileo is the founder of the science of Dynamics. From the date of his first appointment to a university post in 1589 until his discovery of the astronomical telescope in 1610 he was chiefly occupied with the study of mechanics. From 1610 to 1632 his studies were mainly astronomical, but for the last ten years of his life, after his condemnation by the Inquisition, he returned to mechanics once more. His work on falling bodies, on projectiles, machines and the pendulum represents a higher flight of genius than his astronomical discoveries; for the latter depended greatly on the chance invention of the telescope.

When Galileo was Professor at Pisa it was taught in all universities that Aristotle had said that the velocity with which a body fell to the ground was proportional to its weight—e.g. that a 10–lb. shot fell ten times as fast as a 1–lb. shot. This is not precisely what Aristotle said, though it probably represented his belief. A picturesque and famous story is told by Galileo's biographer, but the evidence for it is very shaky. Galileo is said to have climbed to the top of the leaning tower of Pisa and, before

a large assembly, to have let fall simultaneously a heavy and light weight, which both reached the ground together. The story runs that the philosophers who witnessed it remained for the most part unconvinced, Aristotle's pages being more convincing than the evidence of their own eyes. There is nothing improbable in the story except the fact that it remained unmentioned till half a century after it is said to have occurred. Stevinus of Bruges certainly performed such an experiment before the year 1586, and many authors had disputed Aristotle's view. Be this as it may, such a spectacular demonstration would have been but a small matter compared to the discovery of the laws governing the rate of falling bodies. By setting a ball rolling down an inclined plane and timing it with a water-clock, Galileo found that the distance travelled varied as the square of the time of descent. He showed that the path of a projectile was a parabola and worked out many other dynamical problems. Very important for the progress of Physics is Galileo's analysis of velocity into its factors of space and time. Earlier writers had much confused what we now call velocity, momentum and kinetic energy. Galileo was the first to give precise meanings to some of these terms, a work which was completed by Newton.

Another picturesque but doubtful story is told of his discovery of the properties of the pendulum. It is said that, at the age of eighteen, while praying in the Cathedral of Pisa, he saw a lamp swinging. He timed its swings by the beats of his own pulse and discovered that the time of a single swing remained apparently the same whether the lamp swung through a wide arc or a narrow one. He then investigated the matter systematically and confirmed this result. Many years later, in his old age, he designed

a pendulum-clock. However, the invention was not perfected, and the first pendulum-clock was made, independently, by Huygens in 1656.

Huygens carried on the work of Galileo and made a study of pendulums and of inertia, but the chief honour of establishing the science of Mechanics belongs to Sir Isaac Newton (1642–1727), who in his *Philosophiæ Naturalis Principia Mathematica* defines the concepts of force, momentum, acceleration, etc., which are essentials not only to this science but to every other. Newton worked out the laws of motion of bodies with great thoroughness; later mathematicians continued the working out of his principles in elaborate detail. The subsequent history of Mechanics belongs rather to mathematics than to science and can hardly find a place here. It must not be forgotten, however, that much of the achievement of Astronomy and of Engineering depends on the mathematical treatment of Newton's fundamental concepts.

THE NEW PHYSICS, 1600–1850

The other departments of Physics were brought, during the period 1600–1850, from a state almost of non-existence to that of recognisable rudiments of the science in its modern aspect.

Thus in the study of heat the notion of the existence of an element of fire, or of fiery atoms, was destroyed and the ideas of temperature and of quantity of heat were established. The erroneous notion of heat as an imponderable material substance—"caloric"—was then set up, and in the nineteenth century gradually gave way to the modern theory that heat is a motion of particles. This

was not generally accepted before 1850, and only thereafter was established the Kinetic theory of heat, which made thermal phenomena amenable to mathematical treatment.

Light was studied and optics made great advances. The corpuscular theory of light, advanced by Newton, was in conflict with the undulatory or wave theory of light advanced by Huygens. The latter in an altered form began to gain ground about 1815 and was established with certainty only in 1850. Not until 1870 was it established that light was an electromagnetic phenomenon.

In the study of magnetism and electricity, which begins with William Gilbert's *De Magnete* (1600), the notion of imponderable "electric fluids" was adopted as a means of explaining the phenomena. The explanation of electricity in terms of separate and ponderable electrons had to wait till near the end of the nineteenth century. The year 1850, however, again marks an important stage—the beginning of the practical use of electromagnetic induction. The dynamo, motor, transformer, induction coil and telegraph all date from a period near 1850, which in this sense is the beginning of the Age of Electricity.

THE PHYSICS OF GASES, 1600–1850

The study of the physical properties of air aroused the greatest interest in the seventeenth century. The notions prevailing before that time as to the nature of air had been of the vaguest, and there was no great certainty that air was a real material substance in the same way as was earth or water. Opinions had been expressed that air had weight, but they were not submitted to test until Galileo showed that a glass bulb filled with compressed

air was heavier than the same bulb filled with ordinary air. Aristotle had proved at great length that a vacuum was impossible, and the fact that water or air would rush in to fill any space which had been made empty—e.g. by withdrawing the piston of a syringe—was explained by the maxim that "Nature abhorred a vacuum." This was obviously an unscientific explanation. The experiment devised by Torricelli (1608–47) and carried out by a pupil in 1643 was a crucial one. It was known that a suction pump would not raise water more than about thirty-three feet. Torricelli knew that air had weight and saw that it was possible that the air exerted such a pressure as would uphold a column of water thirty-three feet high, but no higher. He advocated the filling of a long glass tube with mercury and inverting it in a trough of mercury; when this was done, the mercury fell till the column was some thirty inches high. The space above it was clearly a vacuum. The news of this experiment reached France, and Pascal in 1646 confirmed the idea that it was the air which upheld the mercury, by taking the apparatus up a mountain, whereupon the mercury fell three inches. The doctrine of Nature's abhorrence of a vacuum was exploded.

The next stage was the invention of the air-pump by Otto von Guericke of Magdeburg (1602–86) who had not, however, heard of the work of Torricelli. His first method was to pump the contents out of a closed vessel containing water, so leaving a vacuum: later he invented an actual air-pump and performed the first experiments on the vacuum. The properties of air were overlooked in earlier times, because air was universally present. Once a space containing no air was available, the properties of air were soon demonstrated. Otto von Guericke showed the great pressure of the air by his famous experiment of

exhausting two accurately fitting copper hemispheres about fifteen inches in diameter, whereupon a team of sixteen horses was needed to pull them apart. Plate VII shows his method of measuring the force of the pressure of the air, by finding the weight needed to pull the evacuated hemispheres A, B, apart. He strengthened Galileo's demonstration that air had weight by weighing a vessel, first when filled with air, then when exhausted. He showed that sound was not transmitted by the vacuum, that birds and fishes cannot live without air and that flames go out in an exhausted vessel.

Guericke's experiments became known to Robert Boyle (1627–91) for whom Hooke, who was for some time his assistant, made a better air-pump. Boyle showed that the barometer fell to near zero in the receiver. He made very extensive experiments on combustion and respiration in evacuated spaces, but his greatest work was the discovery of the elasticity or "spring" of air and the establishment of Boyle's Law, which states that the product of the volume and the pressure of a gas is constant, e.g. that if the pressure on a gas is doubled, its volume is halved and *vice versa*. Boyle also succeeded in weighing air with fair accuracy.

After this time little work of importance was performed upon the physical properties of gases until the beginning of the nineteenth century when J. A. C. Charles (1746–1823) discovered the law which governed their expansion by heat. He did not publish this, and it appeared in the work of Gay-Lussac, published in 1802. The law, now known as Charles' Law, states that for all gases the expansion per degree is a constant fraction of the volume at some arbitrarily fixed temperature. Thus a gas expands or contracts by 1/273 of its volume at 0°C. for each

degree Centigrade its temperature is raised or lowered.

Regnault (1810–78), a worker of brilliant accuracy, showed that Boyle's Law was not exactly obeyed by any gas and that all gases except hydrogen, when compressed, contracted to a rather greater extent than the law indicates.

The liquefaction of gases was chiefly due to Faraday, who caused various gases to be evolved from solids or liquids contained in one limb of a glass tube shaped like an inverted V, the other being cooled with ice and salt. By simultaneous cooling and compression he caused carbon dioxide, hydrogen sulphide, hydrogen chloride, chlorine and several other gases to liquefy: other workers followed him and soon succeeded in liquefying all known gases except hydrogen, oxygen, nitrogen, carbon monoxide and methane, all of which resisted liquefaction until near the end of the nineteenth century.

ELECTRICITY AND MAGNETISM, 1500–1850

The fact that amber (in Greek *elektron*), when rubbed, acquired the power of attracting light objects such as dust-particles or bits of straw was known to the ancients, as was also the lodestone's power of attracting iron. A host of false opinions gathered about the latter: thus it was believed that goat's blood would destroy its power of attraction, and that the diamond would magnetise iron.

William Gilbert of Colchester (1540–1603) published in the year 1600 a work *De Magnete* which was as remarkable for its scientific spirit as for its content. He abuses with Elizabethan freedom the credulous copyists of vain tales, and appeals to the experimental method as the sole

FIG. 18
The magnetisation of an iron bar when hammered in a N.–S. position.
(From William Gilbert's *De Magnete.* 1600.)

way of finding the truth. Gilbert first explodes a great number of fallacies concerning the attraction of the magnet and of electrified bodies. This was very necessary work, but his greatest contribution was the notion that the earth is a vast magnet. He made little globes out of lodestone and showed that they influenced compass-needles in the same way as did the earth. Gilbert established experimentally many of the elementary facts about magnetism. His enthusiasm for his subject led him to speculate as to the cause of magnetic attraction. He thought of it as a sort of effluvium or soul, somewhat similar to the influence the planets were believed to have upon man. He attempted to show that the rotation of the earth was a result of its magnetic properties. His work ranks with

that of Galileo as among the first in which the experimental method was applied to Physics. Galileo regarded Gilbert's work with enthusiasm and declared himself envious of it.

Not much progress could be made in the study of electricity until an adequate means of producing electrical effects had been devised. Otto von Guericke (p. 145) made an electric friction machine in which a rotating globe of sulphur was rubbed and the electricity drawn off. In this way a few of the properties of static electricity were demonstrated. In the early eighteenth century the distinction was made between conductors and non-conductors. Du Fay (1698–1739) discovered that all bodies could be electrified by friction: he also distinguished between the two kinds of electrification, which were later called positive and negative. Electricity was regarded as a weightless fluid, an idea which presented no difficulty to the eighteenth-century mind. The quantities of electricity produced by these simple frictional machines were very small: an important step was the discovery of the Leyden jar in 1740, and, simultaneously, of the electric shock. This attracted the greatest interest and numerous experiments were conducted which for the most part were scientific recreations rather than researches. Benjamin Franklin in America became interested in electrical phenomena and proposed a theory of them which was nearer the truth than were any earlier ones. He suggested that there were not in fact "two electric fluids, but only one." What had been called *vitreous* electrification he thought to consist in the presence of an *excess* of electric fluid, while the *resinous* electrification consisted in a *deficit* of the same. To these states he applied the terms positive and negative electrification. Franklin

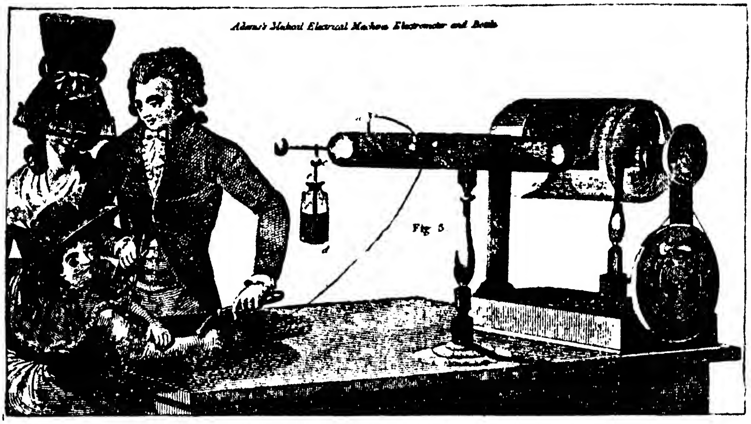


FIG. 19
The medical use of electricity was popular in the late eighteenth century. Above is shown a frictional machine and Leyden jar used for such a treatment. (Hall's *New Royal Encyclopædia.* 1790.)

proved spectacularly, by means of a kite and a thunder-cloud, that lightning was an electric spark, and later invented the lightning conductor.

The next great step was the attempt to apply measurements to electric phenomena. Cavendish made remarkable discoveries in this field, which, however, he did not publish. Coulomb in 1785–1789 showed that Newton's Law of Inverse Squares (p. 190) applied to electrical attraction. This had also been done at an earlier date by Priestley.

All studies of electricity which had hitherto been made dealt with minute quantities of electricity at very high potentials. The discoveries of two Italians, Galvani (1737–98) and Volta (1745–1837), gave us the electric battery with its power of producing a continuous current of large quantities of electricity at a low potential. The discovery was made in the oddest manner.

In 1780 Galvani noticed that when electricity was

applied to the nerve of an isolated frog's-leg the muscles contracted—itself a most important biological discovery. He later found that if a bent rod, composed of two different metals, was allowed to touch a nerve and a muscle simultaneously, the same effect occurred. Galvani was inclined to believe that the contraction was caused by electricity which had originated in the nerve. Volta proved that the association of two different metals in contact with a conductive liquid could produce electricity, and constructed the first electric battery. The voltaic cell in its simplest form is a vessel containing dilute acid into which dip strips of zinc and copper. If these strips are connected by a wire an electric current flows. The voltaic cell was rapidly improved, and other combinations of metals and liquids were tried. The usual form in which it was applied was the voltaic pile which commonly consisted of hundreds of discs; first a disc of copper, then a disc of flannel moistened with brine, then a disc of zinc, then another disc of copper and so on. Each set of discs produced a small potential difference and a pile of some hundreds of these gave a potential difference of a hundred volts or more. Volta published his work in 1800. Its results were far-reaching, for as a consequence of the discovery of an adequate source of current the phenomena of electrolysis, mentioned on p. 181, were soon discovered by Sir Humphry Davy and others and the connection between electrolysis and chemical combination (p. 182) was discussed by Grotthuss and Berzelius. The current furnished by the voltaic cell rapidly fell off owing to polarisation, and it was not until 1836, when Daniell invented the cell that bears his name, that a more efficient cell became available.

Meanwhile the interaction of magnets and the electric

current was widely studied. Oersted in 1819 showed that a wire carrying a current deflected a magnetic needle lying parallel to it. In the next year Schweigger invented the galvanometer, which consisted of many turns of wire surrounding a magnetic needle, the deflection of which gave a measure of the quantity of electricity. In the next few years, galvanometers were greatly improved. Ampère discovered that parallel currents attract each other and studied more closely the manner in which magnets were deflected by electric currents. In 1825 Sturgeon made the first electromagnet, which Joseph Henry, in America, considerably improved.

The work of Faraday (1791–1867) upon the relation between electricity and magnetism proved to be of the greatest importance. In 1831 he discovered that when a magnetic field was excited in proximity to a coil of wire, a current momentarily flowed in the coil; he also showed that when a current was stopped or started in a wire it would *induce* a current in a second wire lying parallel to the first. Henry in America probably anticipated Faraday in the first of these discoveries, and also showed that currents of high voltage could be induced by those of lower voltage. About 1840 Page, in America, constructed the first practical induction coils, but his results were unknown in Europe, where it was not until 1851 that Ruhmkorff succeeded in producing an effective induction coil.

The idea of a field of force surrounding electrical charges or magnetic poles had gradually arisen and had been treated mathematically by Ampère. Faraday gave a visual picture of this field by supposing that there existed throughout the field *lines* or *tubes of force* pointing in the direction in which the magnetic or electrical force acted.

Faraday believed these lines had a real existence, and they certainly are a most useful conception. Faraday's work also laid the foundation for the theory that light is an electromagnetic vibration, which was established between 1861 and 1873 by the genius of Clerk Maxwell: this work is further considered on p. 256.

Most of the fundamental electrical phenomena were known in principle by 1850; the work of the second half of the nineteenth century was to establish the mathematical theory of electrical phenomena and to make hundreds of important practical applications of the simple principles known in 1850. In the twentieth century the nature of electricity became more nearly known and the discovery of the electron opened up a new field, among the practical fruits of which are X-rays, radio, and television.

THE STUDY OF LIGHT, 1500–1850

The ancients, and after them the Arabs, had worked out the elements of the study of optics. Reflection had been well studied, but the laws which governed the refraction of light by prisms and lenses remained unknown until the seventeenth century. Kepler studied the refraction of lenses and gave a fair explanation of their working. In 1621 Snell, Professor of Mathematics at Leyden, gave the correct law, but did not publish it; Descartes in 1637 also arrived at the correct law, by deducing it from three assumptions, two of which were in fact incorrect!

There is much dispute as to the discoverer of the telescope. It seems clear that the first true telescope was made in Holland in 1608 and that Galileo heard that an instrument capable of magnifying distant objects had been

invented and discovered for himself the means of making one. Galileo's instruments had a concave eye-piece and a convex object-glass and their field of view was rather small: Kepler in 1611 set out the advantages of a telescope constructed (as is the modern type) of two convex lenses. Kepler's telescope was not, however, very quickly adopted, but in the middle of the seventeenth century it came into general use, largely because of its wider field of view. To increase the magnification of these, the length was continually increased, and in the late seventeenth century telescopes over one hundred feet in length were employed.

Newton was led by the experiments described on p. 156, to suppose that every lens must necessarily refract the component rays of white light to a different extent: it therefore seemed to him that a telescope composed of lenses was bound to show coloured fringes round the image. He therefore constructed the first reflecting telescope (1670) in which a concave mirror replaces the convex lens of the object-glass of the refracting telescope. The invention lay neglected for fifty years, when the idea was again taken up and reflecting telescopes became popular. The final step was the perfection of the refracting telescope in consequence of Dollond's discovery of achromatic lenses.

The microscope was invented at about the same period. Simple lenses had been known from early times, and by making these small enough very great magnifications could be obtained. Antony van Leeuwenhoek (1632–1723) succeeded in discerning by their aid objects such as spermatozoa and possibly even bacteria.

Modern compound microscopes consist of several lenses. The forerunner of these was probably discovered

by the Janssen brothers in Holland about 1590: it had a convex objective and concave eye-piece. Convex eye-pieces soon followed. The development of the microscope runs parallel to that of the telescope. Newton proposed a reflecting microscope, having mirrors in place of the usual lenses; but the idea was dropped when the making of achromatic lenses became a practical proposition.

While these optical instruments were being perfected much was being discovered as to the nature of light itself. The greatest optical achievements of the years 1600 to 1850 were first, the accurate measurement of the velocity of light, in earlier times thought to be infinite, secondly the solution of the problem of the nature of colour, a notable progress towards the discovery of the nature of light.

The velocity of light was first estimated by the Danish astronomer Römer. The time of revolution of Jupiter's satellites round the planet was known with much accuracy, but actual predictions of the moment of their eclipses were not accurate. Römer saw that if light took time to travel, the eclipse should appear to take place earlier when the earth was near Jupiter than when the earth was far from Jupiter. From the expected and observed times he calculated a value for the velocity of light which was, however, too low by about 40 per cent. The novel idea of the velocity of light was received with some doubt, but Bradley (1726) confirmed Römer's work and reached a much more correct result. No determination of the velocity of light was made by other than astronomical means until the year 1849.

The problem of the nature of colour was solved by Newton in 1676. The formation of colours from white light had been noticed before his time, but not scientifically investigated. Newton allowed a ray of sunlight to

pass through a hole in the shutter of a dark room and then through a prism, whereby it was expanded into the band of coloured light now familiar as a spectrum. Newton showed that if this coloured light was passed through another prism, it could be caused to recombine to form white light; and that, consequently, white light was *a mixture of different coloured rays some of which are more powerfully refracted than others.* He concluded that all refraction was accompanied by this unequal bending of rays, and that it was therefore impossible to make an optical instrument which was achromatic, i.e. which gave an image without colour-fringes. Here he was too hasty, for the problem was solved in 1758.

What was the difference, he reflected, between light of different colours? In 1665 Hooke had put forward an outline of a wave theory of light: this was not identical with the modern view in that the waves were thought of as longitudinal like sound waves, not transverse like water waves. Huygens, a little later, had brilliantly explained reflection and refraction in terms of this undulatory theory. Newton saw that this theory could explain the difference between the colours of soap-films, etc., but he could not see how a wave motion could be propagated in a straight line without spreading out on all sides. Light does, in fact, spread out in this way, as Grimaldi (1666) had observed, but Newton evidently had not contemplated the idea that light waves were so minute as to give only the small spreading-effect observed.

Many theories of the nature of light had been held; the idea that it consisted of particles dated back to the Pythagoreans (p. 24). Aristotle, however, thought light was some sort of action transmitted by a medium. Other authors thought it was something which proceeded

from the eye. Newton accordingly gave precision to the ancient *emission* theory of light. A luminous body, he postulated, emitted streams of minute particles which constituted light. This theory could explain refraction if it were supposed that when the particle passed from a rarer to a denser medium (e.g. from air to glass) the attraction of the latter increased its velocity. The undulatory theory on the other hand indicated that the velocity in the denser medium should be less. This was not settled by experiment until 1850, when Foucault showed that the velocity of light was less in water than in air. The emission theory was an article of faith throughout the eighteenth century, and light was thought of as a material substance. It even appears in the lists of chemical elements made at the beginning of the nineteenth century. In the early nineteenth century the experiments of Thomas Young and of Fresnel showed that two rays of light could "interfere", causing darkness. The undulatory theory could explain this as being due to the "troughs" of the waves of one ray coinciding with the "crests" of the waves of the other, but the emission theory could offer no convincing explanation. Again, polarisation could be explained if light consisted of transverse waves but not if it consisted of particles or of longitudinal waves. Thus the emission theory rapidly lost favour from about 1815, and Foucault's experiment, mentioned above, settled the question in 1850.

In the second half of the eighteenth century the great invention of the achromatic lens was made. Newton, as we have seen, thought achromatic lenses impossible and therefore resorted to the reflecting telescope which uses a large concave mirror in place of an object-glass.

In the eighteenth century, however, the problem was

solved. The mathematician Euler suggested the use of two different kinds of glass in the same lens, and Dollond in 1758 made the first achromatic telescope, by using a lens made up of two lenses, one of which was a convex lens of crown-glass and the other a concave lens of flint-glass. These achromatic lenses were not perfectly free from colour fringes, but were greatly superior to the simple lens.

The study of the spectrum was taken up in the nineteenth century with improved instruments and spectral lines were noticed by Fraunhofer (1814). Spectra were further examined, but the notion that each of the lines in the spectrum of a flame of a star could be attributed to the presence of some one of the various elements in the glowing gas from which the light proceeded, had to wait till the work of Bunsen and Kirchhoff in 1859.

The notion that the region of the spectrum beyond the red contains radiation like light but invisible was brought forward in 1800 by Sir F. W. Herschel. Our knowledge of this radiation was advanced by Sir John Leslie between 1800 and 1825, but its systematic study had to wait for Melloni's great work published in 1850.

The beginning of practical photography, on which so much of modern seience is based, dates from *c.* 1837, but its influence was hardly felt before the second half of the nineteenth century.

THE NATURE OF HEAT, 1600–1850

Up to the seventeenth century no clear idea had been formed as to the nature of heat. The element "fire" was held responsible for the phenomena we call heat, fire and

flame. The atomic view of matter substituted for the element "fire" a concourse of subtle fiery atoms or particles capable of inter-penetrating the material atoms of a body.

Francis Bacon rather vaguely envisaged the notion that heat might be a vibration of atoms, and Boyle also took this view and instanced the heating of iron by hammering it; however he still occasionally speaks of fire-atoms. Hooke strongly advocated the idea that heat was an agitation of the parts of a body. At this early period some

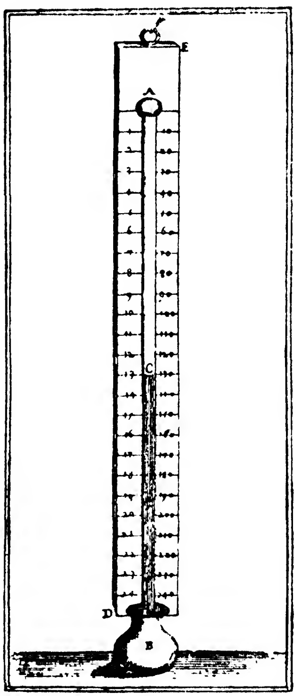


FIG. 20

An air-thermometer of the type invented by Galileo. (From Bettinus. *Apiaria Universae Philosophiae Mathematica.* 1642.)

studies of radiation were also made. Mariotte and Hooke both showed that from a ray conveying both heat and light the former can be screened off, e.g. by glass.

Galileo had invented a simple air-thermometer consisting of a glass bulb containing air joined to a long tube partly filled with a coloured liquid and dipping into a vessel of the same liquid. Such a thermometer is very sensitive, but is unreliable because the volume of the air contained in it is affected by changes in atmospheric pressure as well as by changes of temperature. Sealed alcohol-in-glass thermometers, not unlike those of to-day, were employed in Italy about 1660. The mercury-in-glass thermometer was also tried out but was not at first found successful. These early thermometers are to be regarded rather as indicators of temperature changes than as measurers of them, and no satisfactory way of marking them with a reproducible scale had been reached. Sir Isaac Newton in 1701 proposed taking two fixed points, the freezing-point of water and the temperature of the human body and dividing the interval into twelve degrees. Römer, the astronomer, worked on this problem, but Fahrenheit from about 1714 onward succeeded in solving it. Fahrenheit showed that a mixture of ice and water always assumed the same temperature and, later, that water always boiled at the same temperature provided that the barometric pressure was the same. The melting-point of ice and the boiling-point of water were finally adopted as the fixed points of the thermometer and were given the values of 32°F. and 212°F. respectively; these numbers were chosen by Fahrenheit because in his earlier experiments he had defined the temperature of the coldest freezing mixture he could obtain as 0°F. and that of the human body as 96°F.; this brought the freezing point of

water to about 32° and its boiling point to about 212°. There was much scope for choosing fixed points and in fact some thirteen different scales were proposed. The scale which survives in the Centigrade thermometer, on which the melting-point of ice is shown as 0°C. and the boiling-point of water as 100°C., originated with Linnaeus (p. 200) before 1737, and was independently invented more than once. Up to the middle of the nineteenth century great uncertainty prevailed as to the measurement of temperatures above the boiling point of mercury.

In the eighteenth century the correct notion that heat was an agitation of atoms went out of fashion, and the view was taken that heat was a form of matter, imponderable, highly elastic and having particles which repelled each other strongly. This "subtle fluid" was named *caloric*, and the belief in its existence persisted until the middle of the nineteenth century. Caloric is to be found in the earlier lists of chemical elements.

The distinction between temperature and heat was made clearer by the work of Black (*c.* 1756) who showed that some substances needed greater quantities of heat to raise them through a given range of temperatures than did others, and also that in the melting of ice or the changing of boiling water into steam large quantities of heat were taken up without changing the temperature of the material at all. James Watt studied the latent heat of steam at about the same period and on it founded his epoch-making improvements in the steam-engine (p. 221).

About 1800 a very important step was taken towards the knowledge of the real nature of heat. Benjamin Thompson (Count Rumford), the founder of the Royal Institution, noticed the great quantity of heat evolved by friction

during the boring of a cannon. He drilled a mass of metal immersed in water, using a blunt borer, with the result that the friction raised about two and a half gallons of water to the boiling-point in about 2½ hours. Here was evidence that heat was being created. The only thing put into the apparatus was *motion,* so Rumford concluded rightly that heat was motion. The believers in the theory that heat was the material imponderable substance, caloric, maintained that the dust or filings of metal produced in the operation contained less caloric than the intact metal and that therefore caloric was expelled by the friction. Alternatively it was thought that the compression of the metal expelled caloric. Sir Humphry Davy confirmed Rumford's view by an apparatus which automatically rubbed two pieces of ice together in an evacuated receiver kept at 0°C. Part of the ice was melted and the heat was here clearly supplied by motion.

These seemingly conclusive experiments made few converts, probably because no theory of the nature of the internal motion which constituted heat could then be advanced. But from the years 1848 onward the work of William Thomson (Lord Kelvin) and others developed a mathematical theory of heat as a motion of atoms in such a way that its truth could not be doubted, though even in 1856 the writer of the article on HEAT in the *Encyclopaedia Britannica* favours the caloric theory.

THE STUDY OF SOUND, 1600–1850

The discovery of the Pythagoreans that the pitch of a musical note depended in a mathematically expressible way on the length of the string that produced it, was perhaps the first discovery of scientific physics (p. 24).

Throughout all ages of civilisation musical instruments had been constructed and much practical knowledge had been obtained. That the pitch of a musical note depended on the number of vibrations in a given time was shown by Galileo, who drew a sharp iron across a brass plate. A musical note was produced, and fine lines were seen indented in the brass, each corresponding to a vibration. (The phenomenon may be very easily demonstrated by drawing a wet finger over a window pane.) By counting the lines produced in a given time, he estimated the rates of vibration corresponding to particular notes. It had usually been recognised that air was the medium that transmitted sound. Otto von Guericke, inventor of the air-pump, proved this by ringing a bell in the receiver and showing that the sounds became feebler as the air was exhausted. Hauksbee in 1705 showed the contrary effect, namely that compressed air transmitted sounds very distinctly.

Vibrating strings were much studied in the late seventeenth century and mathematical formulæ connecting their weight, tension and rate of vibration were worked out. At this period the complex vibrations of strings which produce overtones were studied.

That sound had a measurable velocity must have been obvious from the earliest times. In the seventeenth and eighteenth centuries this was several times measured, by timing the interval between the flash of a cannon and the perception of the report. Newton worked out from mechanical principles what the velocity should be, but his result was a good deal lower than experiment indicated. The reason for the discrepancy was that he did not realise that the heating effect of the compression waves altered the elasticity of the air.

CHEMISTRY AND THE NATURE OF MATTER, 1500–1850

The official view held from the beginning of the Christian era until the seventeenth century was that matter was a homogeneous composition and infinitely divisible. All things consisted of a single prime matter, which could not be obtained by itself in a pure condition. On this were super-imposed the "elements" or *earth, air, fire* and *water,* which represented the qualities of coldness and dryness, heat and moisture, heat and dryness, coldness and moisture respectively. Thus everything was first of all material, then hot or cold, moist or dry, in varying degree. In addition matter had accidental properties, e.g. of colour, density, odour, transparency, etc.

The study of alchemy by the Arabs directed particular attention to metals and, since Aristotle's earth, air, fire and water did not explain the peculiar qualities of metals, the theory was evolved that *mercury*, a metallic and volatile principle, and *sulphur,* a fiery and combustible principle, were the elements from which metals were derived. Paracelsus extended this theory to all types of matter by adding to these two principles *salt*—a dry earthy quality. Up till late in the eighteenth century some selection of these seven "elements" were generally thought to be the constituents of matter.

From these ideas it followed that transmutation was possible, for all substances had a common basis. Yet Aristotle had distinguished different *species,* which were considered to be eternally immutable. But even if the metals were *species,* they could in theory be transmuted by removing the superimposed elements and so converting them to their first matter, and then reconverting this into the new metal.

These theories of matter were supported by very little evidence. No one knew exactly what was meant by the "elements" of earth, air, fire, water, sulphur, salt, and mercury, and the theory was useless as a means of predicting chemical phenomena.

The theories of Democritus (p. 42) were, however, at no time altogether extinct. The Democritan view was that matter was composed of indivisible atoms, and that the differences between the various kinds of matter were occasioned by differences of size and shape in the atoms which composed it. This theory was not supported by appreciably stronger evidence than the other. The centuries from 1600 onward were however to provide increasingly strong evidence of its substantial truth.

Chemistry before 1500 (except in so far as some practical arts such as pharmacy and metallurgy may be called chemistry) was identical with alchemy and was centred upon the problem of transmuting metals. Its progress was slow, and the secret character of alchemy led to a style of description which was calculated to obscure rather than to elucidate. Paracelsus, who in obscurity and conceit of words yields to no previous chemist or alchemist, made a singular advance in urging that the powers of the chemist should be directed to the preparation of medicines, mostly of mineral origin. He thought the potency of drugs was dependent on the extent to which they had been freed from extraneous matter: by efforts directed to this end his disciples contributed to the formation of the fundamental chemical notion of a *pure substance*. He himself made no great discoveries, but between 1550 and 1650 his followers such as Libavius, van Helmont and Glauber discovered many new chemical compounds, though without much scientific method to guide them.

The works of "Basil Valentine" were published in 1603–4. They were believed to have been written by a Benedictine monk about 1470, but they were almost certainly written about 1600, by Thölde, a German salt manufacturer. They describe many new compounds, notably of antimony.

Van Helmont (1577 or 1580–1644) was the greatest precursor of scientific chemistry. He devoted himself to practical experiment, and made elaborate studies on the subject of gases; the word *gas* is his invention. He understood that chemical combination—such as the dissolution of a metal in an acid—was not a destruction of the metal, but knew that the metal could be recovered from the solution. It is interesting that such a reliable and scientific author should leave a careful description of a transmutation of mercury into gold, which, he says, he performed himself with a portion of the Philosopher's Stone which was given him.

The atmosphere of secrecy and mysticism which was always associated with alchemy still clings to all the chemical work of this period. Francis Bacon, although his contribution to practical chemical research was negligible, helped to dispel this unscientific atmosphere. He does not deny the possibility of transmuting metals, but treats it as a problem to be tackled by ordinary experimental methods. His works must be thought of as a cause of the scientific attitude to Chemistry which first appeared in the middle of the seventeenth century.

The progress of Chemistry was greatly hindered by lack of clear definitions and descriptions, and the greatest service of Robert Boyle (1626–1691) was to declare that the alchemical method of treating Chemistry as a secret and mystical art was harmful, that the pretensions of the

alchemists were not supported by experiment, and that Chemistry must be treated, like any other science, as a part of the study of nature. Experiments, he urged, must be recorded and a science built up on a foundation of sure fact. Boyle rejected the assertion that the elements of earth, air, fire and water, or of salt, sulphur and mercury, were the ultimate constituents of things; for he could find no adequate evidence that matter could be resolved into them. He considered that there was no reason to limit artificially the number of elements: and to him we owe the fundamental notion that a substance must be regarded as an element until it can be further resolved into simpler substances. Unhappily he made no list of the substances he regarded as elements, and the Aristotelian and Paracelsan way of regarding matter persisted till near the end of the eighteenth century. The new spirit was reflected in the first scientific text-book of Chemistry—that of Nicolas Lemery (published 1675). Boyle's ideas were not perhaps entirely original for similar criticisms had been made by Jungius a few years earlier. This clear and systematic book had enormous popularity and with the text-book of Boerhaave (published 1732) was the source of the chemical knowledge of the eighteenth century.

The main theoretical work accomplished by the chemists of the eighteenth century was the discovery of the nature of air, water and fire—or the phenomenon of combustion. Many of the simplest chemical substances are gases, and little progress in Chemistry could be made until the technique of studying gases was perfected. The word *gas* was invented by van Helmont, who realised that there were gases which differed from air, and that there was a "gas sylvestre" which was given off in fermentation, when charcoal is burnt in air, when cream of tartar is

heated, or when chalk is dissolved in vinegar. This gas is what we now call carbon dioxide. He recognised the existence of several other gases, distinct from carbon dioxide, but since he had no means of collecting these in a pure state, he could not closely examine them. His works were published in 1648 and translated into English in 1662. There is no doubt that they influenced Boyle.

The clear recognition that there were several distinct species of gases or "airs," as they were commonly called, did not become definitely established until a hundred years later, when Cavendish perfected methods for collecting and examining them.

But between 1660 and 1675 three English men of science, Boyle, Hooke, and Mayow, carried out what may be called the first extensive chemical research. We have already seen that the air-pump was invented in 1654. Robert Hooke (1635–1703) was a man of much experimental skill. He devised an improved air-pump and with this he and Boyle established the fact that combustion could not, in general, take place without the presence of air. Nitre (saltpetre) seemed to act in the same way as air, for it was known that gunpowder would burn without access of air and Boyle showed it would burn even in a vacuum. Hooke realised that when combustion took place, the combustible in some sense dissolved in the air (as a metal dissolves in an acid): he considered that air and nitre had a common constituent. John Mayow in his work published in 1674 went still further. He showed clearly that in combustion only a part of the air was used up, this being the constituent common to nitre and air. These men, then, almost reached the true view of combustion, namely that the combustible combines with

the oxygen in the air and leaves the nitrogen unaffected. If they had prepared pure oxygen their case would have been irresistible, but, as it was, their theories were displaced by one which was much farther from the truth—that of the fiery principle *phlogiston*.

Stahl (1660–1734), whose work was based in part on that of Becher (1635–82), set up a theory, which was essentially but little different from the ideas which had been in vogue since the time of Aristotle. The older view of combustion was that the combustible substance contained in itself a "fiery principle," and that, when heated, it broke up and allowed this fiery principle to escape as flame—a very natural view, since flame is to be seen obviously streaming out from burning bodies. The "fiery principle" might be the "fire" of Aristotle, the "sulphur" of the Arabs or the "phlogiston" of Becher and Stahl: the explanation in each case was much the same, in that the theory involves the decomposition of the burning substance with the escape of some fiery principle and does not indicate that air plays any part in combustion.

Stahl conceived that all bodies which would burn, whether with flame, as wood or wax, or by a slower alteration, as copper exposed to heat is converted to a black powder or *calx*, were compound in nature. He considered that all such bodies contained one and the same fiery principle, *phlogiston*, which was evolved when they burnt. For the existence of such a principle quite good evidence was advanced. Thus, lead when heated forms a yellow powder, litharge. On their theory, lead when heated lost phlogiston; metallic lead was therefore a compound, litharge-plus-phlogiston. When litharge is heated with charcoal or almost any combustible, it forms

FIG. 21

Calcination of Antimony in the focus of a burning-glass. (Nicolas Lefévre. *Traite de la Chimie*, 1669.)

metallic lead. This was readily explained by Stahl's theory, for charcoal, being combustible, was considered to contain much phlogiston: this phlogiston would combine with the-litharge and so convert it to litharge-plus-phlogiston, *i.e.*, metallic lead.

This theory was capable of explaining most cases of combustion, but had certain unsatisfactory features. First of all, this phlogiston was very vaguely characterised; by some it was thought of as a sort of fatty earth, others regarded it as a subtle fluid, much like heat, while a few thought it was identical with the gas we now call hydrogen. The dependence of chemistry on a principle which could not be isolated for study was obviously

unsatisfactory. Secondly, it was noticed as early as the sixteenth century that the products of combustion of metals were often heavier than the combustible. If lead *loses* phlogiston and becomes litharge, how could it be that 100 grains of lead when heated produced rather more than 107 grains of litharge? This could only be explained by assuming that phlogiston had a negative gravity, but few, even at that date, cared to assume so exceptional a property for a wholly hypothetical substance. Other facts, too, could not be explained by the phlogiston theory. Air was known to be necessary for combustion. Why would not combustion occur in a vacuum, into which phlogiston would presumably escape as well as into air?

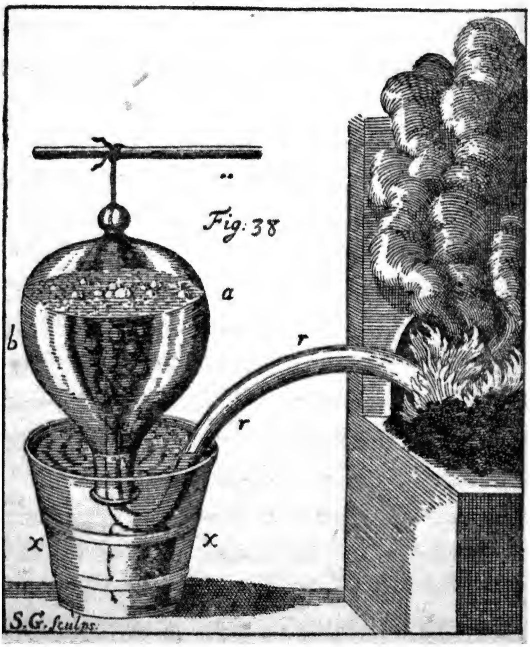


FIG. 22
The first illustration of an apparatus for collecting a gas.
(Stephen Hales. *Vegetable Staticks.* 1737.)

It seems strange to us that these facts did not destroy the theory of phlogiston: however, the theory explained so much that the eighteenth-century chemists preferred to retain it and to hope that some explanation of these matters would finally be found. The overthrow of the phlogiston theory arose, not through its own weakness, but through the satisfying simplicity of the modern view, set out by Lavoisier.

During the period when the phlogiston theory was supreme, the study of gases gave to Chemistry the knowledge and technique required to establish the foundations of modern chemical knowledge. Stephen Hales about 1727 discovered the elements of the technique of collecting gases: he made many of them, including oxygen, but he was only concerned with measuring the quantities of gases evolved from different substances and so missed the conception that different species of gases exist. To Hales all gases were "air."

Joseph Black in 1754 published a series of experiments on the alkalis, in which he established amongst other results that limestone was a compound of quicklime and "fixed air," which we now call carbon dioxide. The significance of this work is, first, his clear recognition that "fixed" air was an individual species of air different from common air and, secondly, the fact that he established clear proofs of his statements by accurate weighing of the substances before and after the changes.

Henry Cavendish, whom we have had occasion to mention in connection with important discoveries in Physics, in 1766 took the next step by making a careful study of both fixed air and inflammable air—later called hydrogen. Cavendish further improved the technique of handling gases, a technique which Priestley finally perfected.

Two great discoverers now came on the scene, namely Joseph Priestley (1733–1804) and Carl Wilhelm Scheele (1742–86). They were alike in contributing nothing of importance to the theory of Chemistry, yet in discovering a great number of substances which were among the simplest and therefore most fundamentally important of chemical materials. Priestley made and recorded a great number of experiments on gases, and discovered hydrogen chloride, sulphur dioxide, silicon fluoride, ammonia, nitrous oxide, and, above all in importance, oxygen. He perfected the means of collecting a gas by bubbling it into an inverted vessel previously filled with water or mercury. Scheele discovered chlorine and sulphuretted hydrogen, and also, independently of Priestley, oxygen, ammonia and hydrogen chloride. He also discovered a great variety of inorganic and organic acids and a number of other compounds.

Priestley and Scheele both performed many experiments with the oxygen gas they had made. They showed that things burned in it with far more vigour than in air, and that it would support the respiration of animals for a much longer period. Priestley regarded the gas as a kind of air which was peculiarly lacking in phlogiston and which was therefore able to take up a very great deal of it from burning substances.

Priestley, Scheele and Cavendish remained convinced of the truth of the phlogiston theory, though they themselves provided much of the evidence which set up the true theory of combustion. It remained for Antoine Laurent Lavoisier (1743–94) to overthrow the theory of phlogiston, inaugurate *La Révolution Chimique,* and to found a chemistry based simply on the combination and decomposition of known substances capable of examination in the laboratory.

Lavoisier put an end to the explanation of chemical phenomena by hypothetical "principles" not subject to the test of experiment.

Lavoisier at once took advantage of Priestley's discovery of oxygen, to which, regrettably, he tried to lay claim. He proved by exact experiments, measuring volumes and weights, that oxygen was a part of atmospheric air, and that when a substance burned it combined with oxygen and therefore became heavier. He also at once realised the significance of Cavendish's proof, in 1784, that when inflammable air (hydrogen) and dephlogisticated air (oxygen) were exploded together water was formed. Cavendish thought this proved that the element water pre-existed in the gases. Lavoisier, who incidentally made no acknowledgment of what he owed to Cavendish, took the important step of stating and proving by further experiment that water—since the time of Thales thought to be a simple substance or element—was in fact a compound of oxygen and hydrogen.

Boyle had defined a chemical element (p. 167), but in fact chemists made hardly any use of the notion before the time of Lavoisier, preferring to explain their work in terms of the various principles of earth, water, air, fire, phlogiston, salt, sulphur, mercury, etc. Lavoisier re-established the idea of an element as being the limit of chemical analysis—a substance which could not be further decomposed. In 1789 he made a list of 33 elements. Twenty-five of these are still regarded as elements; five are oxides, such as lime and magnesia, then impossible to decompose, but now known to consist of a metal combined with oxygen. Lavoisier regarded light and heat as chemical elements, as was rendered necessary by the corpuscular theory of light and the caloric theory of heat.

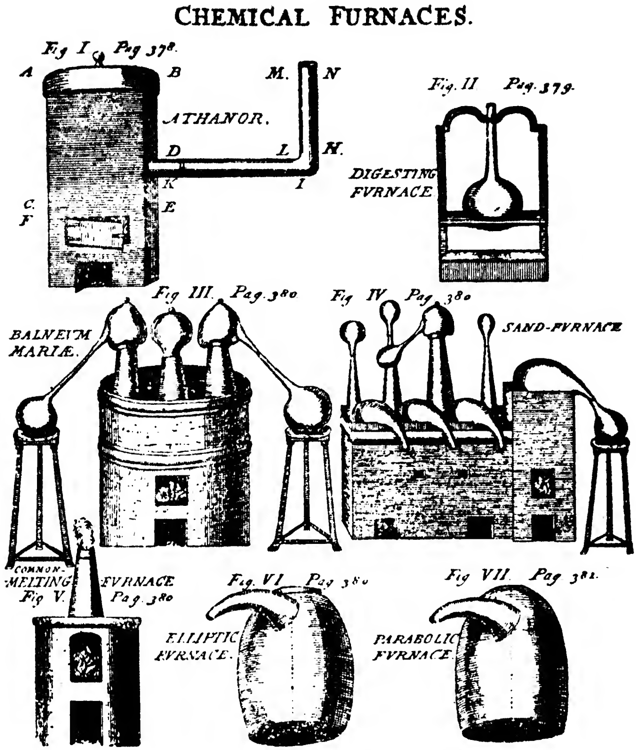


FIG. 23

Chemical apparatus in the eighteenth century. The form of the distillation apparatus has altered little since c. A.D. 300.

He remodelled the whole nomenclature of Chemistry which had previously been based on the notion of phlogiston. To-day the merits of the new system seem to us crystal-clear; in fact outside France it received but slow acceptance, though by the year 1790 it was generally in use. Lavoisier went wrong in supposing that oxygen was the principle of acidity. It was proved in the early nineteenth century that some acids contained no oxygen and that many oxygen compounds were not acids.

Lavoisier was executed by the guillotine in 1794. His

services to science were outweighed by the fact that he had been one of the *Fermiers Généraux*, to whom the taxes had been farmed out by state.

In the closing years of the eighteenth century improvements were made in chemical analysis and it became possible to discover with fair accuracy the proportions of the various elements present in simple substances. This work led to the establishment of the Atomic Theory on which is based the whole system of modern Chemistry. Analyses went to show that all specimens of the same substance contained the same elements in the same proportions, e.g. that every specimen of zinc sulphide contained 67.1 per cent of zinc and 32.9 per cent of sulphur. J. L. Proust, a Frenchman, in 1799 stated this as a scientific Law, laying down that a compound always contained the elements which composed it in a fixed ratio. C. L. Berthollet disputed this view and brought forward facts to show that many substances did in fact vary in composition. Proust's view was finally adopted and the name chemical compound was limited to those materials which were, in fact, of constant composition. Solutions, alloys, glasses, etc., were regarded as mixtures of two or more elements or compounds.

About the same period it became clear that there were other regularities in the proportions in which elements combined. Thus it was found that if a certain weight, say 8 parts, of oxygen combined with, say, 103.5 parts of lead to form lead oxide and 32.7 parts of zinc to form zinc oxide respectively, then a certain other weight, say 16 parts, of sulphur would combine with 103.5 parts of lead to form lead sulphide and 32.7 parts of zinc to form zinc sulphide. Thus 103.5 and 32.7 could be called the equivalent weights of lead and zinc. Various tables of

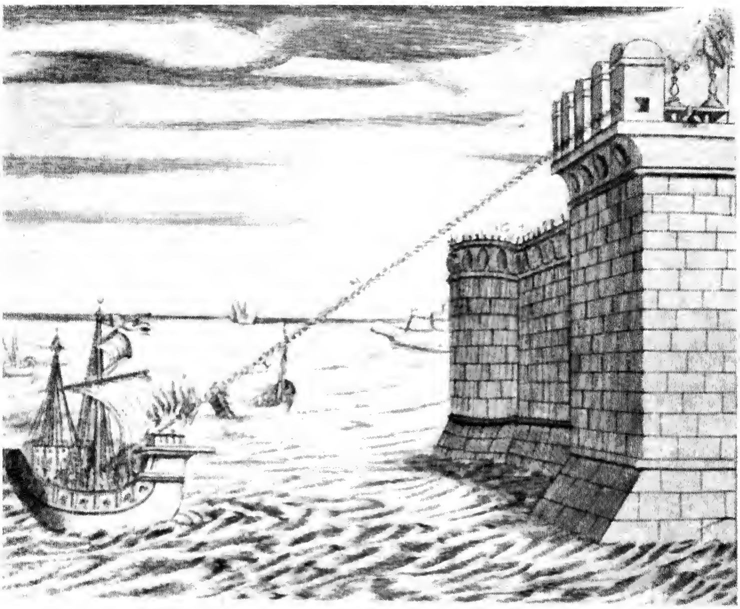


PLATE VIII

In the seventeenth century many untested ideas were published by scientific amateurs and others. The above device recalls the story of Archimedes' burning of the Roman ships. (From Bettinus' ***Apiaria Universae Philosophiae Mathematica.*** 1642.)

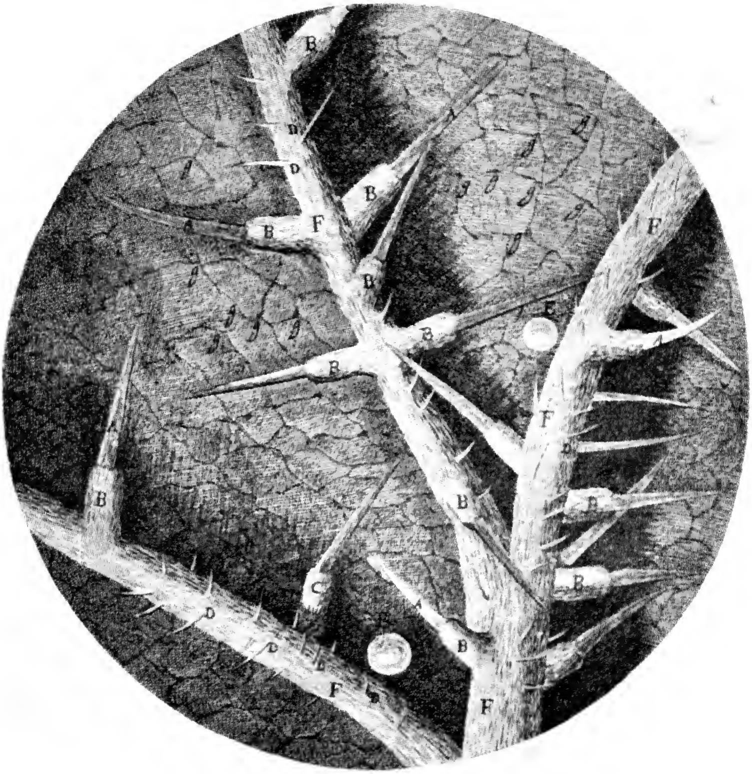


PLATE IX

The stinging hairs on a nettle-leaf from Hooke's *Micrographia*. (1664.)

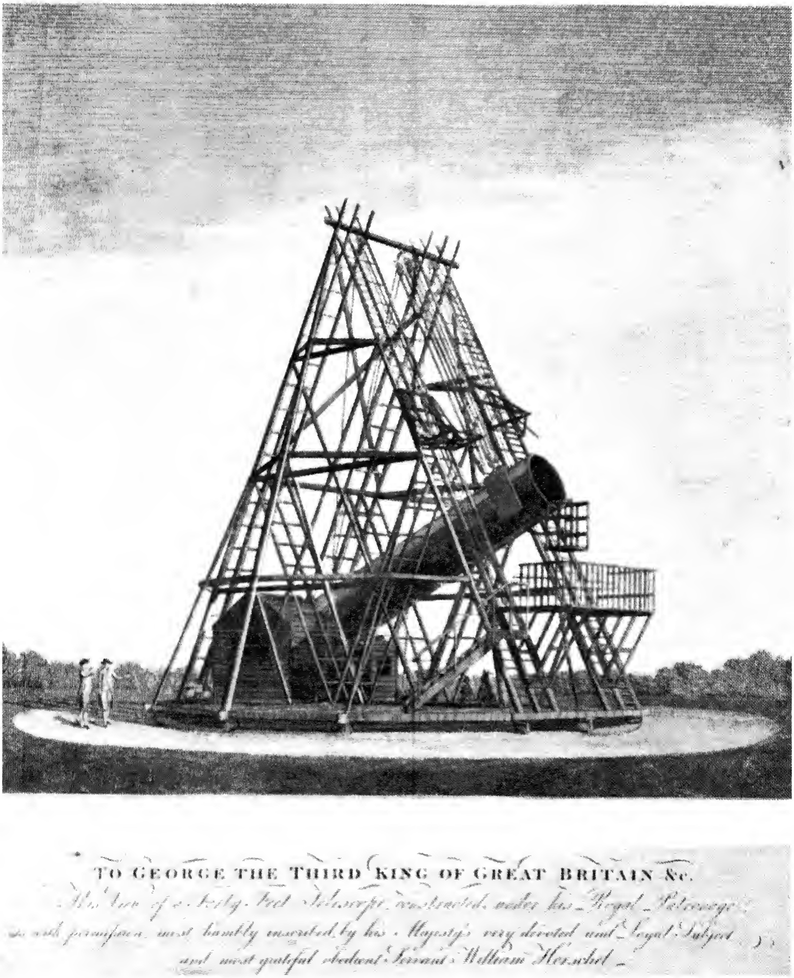


Plate X

Herschel's forty-foot telescope. (1795.)

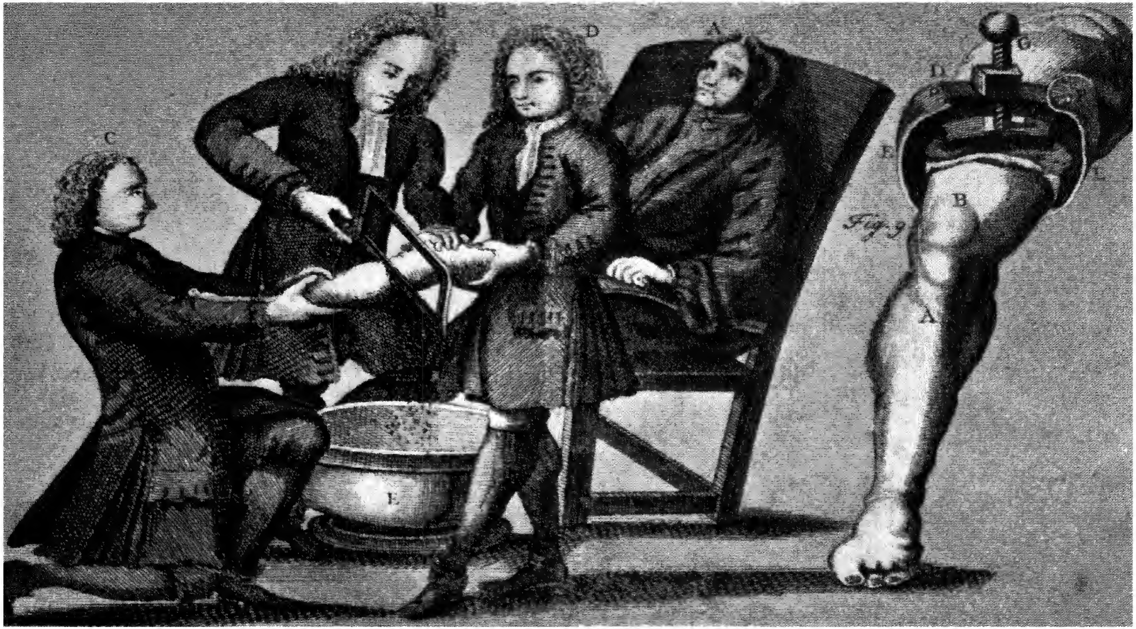


PLATE XI

An eighteenth-century surgical operation. Inset, a tourniquet. (From Lorenz Heister's *General System of Surgery*. English translation. 1743.)

equivalents were published, and J. B. Richter in the years between 1791 and 1795 set out the facts very clearly, and so paved the way for Dalton's enunciation of the Atomic Theory. The ancient theory of the existence of atoms may be even earlier than the time of Democritus of Abdera (470–380 B.C.). It had been revived by Boyle and others in the seventeenth century and Newton had adopted it. The important step taken by Dalton was to make definite suppositions about these atoms and to attribute the varying proportions in which elements combined to the varying weights of these atoms. He seems to have done this about 1802–3, though the work was not published till 1807. In 1808 he published his *New System of Chemical Philosophy* in which his ideas are further developed.

Dalton assumed four simple propositions and showed that they explained all that was known about the proportions in which elements combined. He assumed that:—

1. Atoms are real separate material particles which cannot be subdivided by any known chemical process.

2. Atoms of the same element are similar to one another in all respects, and equal in weight.

3. Atoms of different elements have different properties —weight, affinity, etc.

4. Compounds are formed by the union of atoms of different elements in simple numerical proportions, such as 1:1, 1:2, 2:3, etc.

Let us suppose then, that the smallest particle or *molecule* of lead oxide consists of one atom of lead and one atom of oxygen and that an atom of lead weighs 207 units and an atom of oxygen 16 units. Clearly then each smallest particle of lead oxide contains 207 parts of lead to 16 parts of oxygen and this must also be true of the whole

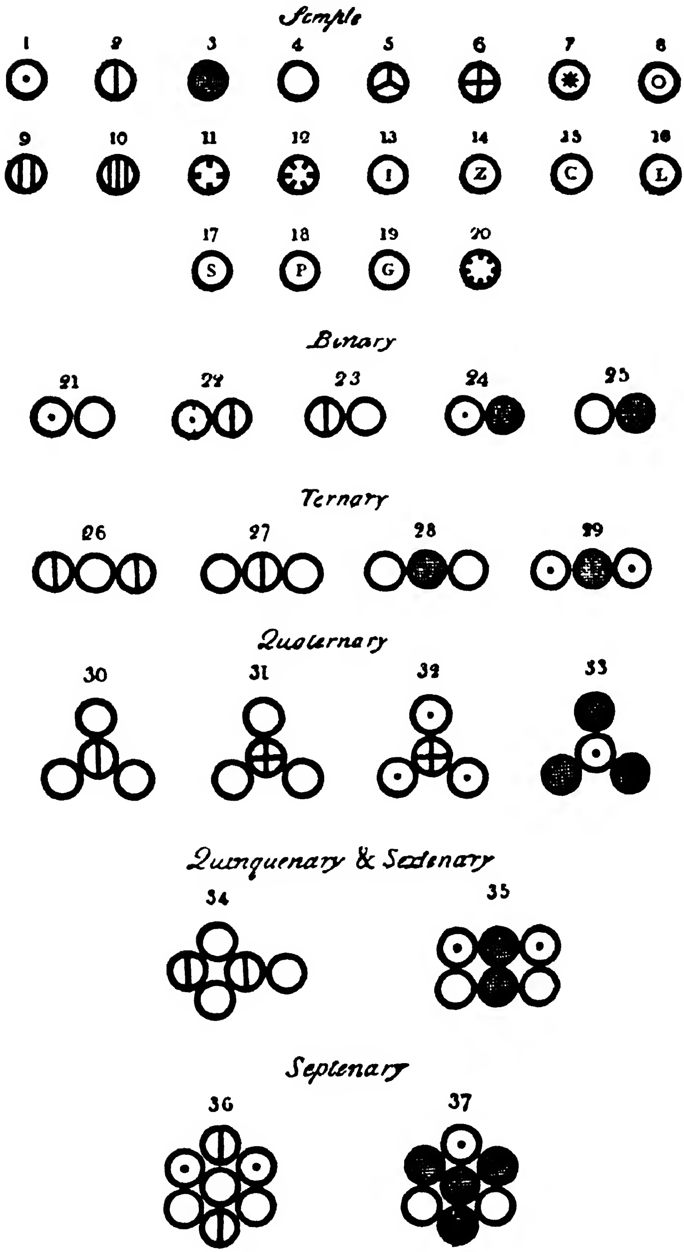
mass of the lead oxide. Thus Proust's law of constant proportions is explained.

Again, take our earlier example of the oxides and sulphides of zinc and lead. Suppose that every zinc atom weighs 32.7 units, every lead atom 103.5 units, and every sulphur atom 16 units and every oxygen atom 8 units. If the compounds are each composed of an atom of metal and an atom of oxygen or sulphur, the regularity noticed is at once explained. Dalton realised that if his theory were correct another regularity should be noticed. Nitrogen and oxygen were known to form a number of different compounds. Let us suppose that the smallest particles of one such compound each contained one atom of oxygen and one atom of nitrogen, and that those of another such compound contained one atom of oxygen and two atoms of nitrogen. Suppose an atom of nitrogen weighed 4.2 and of oxygen 5.5 units.[1] Then in the first compound there will be 5.5 units of weight of oxygen to 4.2 units of nitrogen: in the second 5.5 units of oxygen to 2×4.2 units of nitrogen. In other words, the weights of nitrogen combined in the respective compounds with the *same* weight of oxygen would be in simple numerical proportions, in this case 1:2. This can of course be extended to any case of two elements forming more than one compound. Dalton and others confirmed this prediction by experiment.

[1] From an early table in Dalton's notebooks. The values are much in error.

FIG. 24

Dalton's Chemical Symbols. (1) Hydrogen, (2) Azote, (3) Carbon, (4) Oxygen, (5) Phosphorus, (6) Sulphur, (7) Magnesia, (8) Lime, (9) Soda, (10) Potash, (11) Strontia, (12) Baryta, (13) Iron, (14) Zinc, (15) Copper, (16) Lead, (17) Silver, (18) Platinum, (19) Gold, (20) Mercury, (21) Water, (22) Ammonia, (23) 'Nitrous gas', (24) Ethylene, (25) Carbon Monoxide, (26) Nitrous Oxide, (27) Nitric Acid, (28) Carbon Dioxide, (29) Methane, (30) 'Oxynitric' Acid, (31) Sulphuric Acid, (32) Sulphuretted Hydrogen, (33) Alcohol, (34) Nitrous Acid, (35) Acetic Acid, (36) Ammonium Nitrate, (37) Sugar.


Simple
1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
I Z C L
17 18 19 20
S P G
Binary
21 22 23 24 25
Ternary
26 27 28 29
Quaternary
30 31 32 33
Quinquenary & Sextenary
34 35
Septenary
36 37

From this theory was derived the idea of chemical formulæ on which modern Chemistry is based. Dalton used various symbols (Fig. 24) for the atoms and by putting these together made a picture of the molecules. The symbols were difficult to print, and a more convenient plan of adopting a letter or pair of letters for each atom was put forward by Berzelius in 1813. Thus Dalton wrote a black circle ● for an atom of carbon, which we to-day represent as C; he wrote a white circle ○ for an atom of oxygen which we represent as O. The molecule of carbon dioxide he wrote as ○●○: we represent this as OCO or commonly as CO_2, the subscript figure indicating that two atoms of oxygen are present in the molecule.

Dalton's work did not by any means enable chemists to write the formulæ of all the compounds they could analyse, and much confusion prevailed until the year 1854.

During the first half of the nineteenth century it was well-known that 9 grammes of water contained 1 gramme of hydrogen and 8 grammes of oxygen, so that the weights of hydrogen and oxygen in the water molecule were as 1:8. But it remained doubtful whether the water molecule was made up of one atom of hydrogen of weight one unit and one atom of oxygen of weight eight units, or whether it was made up of two atoms of hydrogen of weight one unit each and one atom of oxygen of weighing 16 units. In the first case the formula was HO, in the second case H_2O. Avogadro in 1811 pointed out the way in which the true formula could be established, but his work was neglected and the first and incorrect formula generally persisted till 1850–60, and was occasionally used as late as 1890. Since the science of Organic Chemistry is almost entirely, and that of Inorganic Chemistry is in great part dependent upon an accurate knowledge of

the numbers and positions of the atoms in the molecules of compounds, the science progressed very much more rapidly in the second half of the nineteenth century than in the first. None the less during the years 1800–50 a great number of new substances were discovered, including most of the simpler substances now known. Most notable are Davy's discovery of potassium and sodium, the metals contained in such important compounds as potash, saltpetre, common salt, soda, etc., and his proof that chlorine was an element. Steady work without much in the way of brilliant discoveries continued, and by 1850 sixty out of the ninety elements now known had been discovered, and their chief compounds had been described.

By the year 1850 the science of Organic Chemistry had been enriched by the discovery of a good many compounds, but its true foundation—the knowledge of the structure of the molecules of its complicated compounds—was not yet laid: it will therefore be taken up in the section devoted to the history of modern Chemistry (pp. 236–250).

In the early part of the nineteenth century some theories were formed about the question—which is even now not wholly solved—as to why atoms combine into molecules. Davy had found that the effect of the electric current was generally to cause chemical compounds to decompose. Thus if two poles, say of carbon, were immersed in a solution of copper chloride and connected to the positive and negative poles of a battery, copper deposited on the negative pole and chlorine gas appeared at the positive pole. Thus chlorine was said to be electro-negative (because attracted by positive electricity) and copper to be electro-positive. Davy thought that some kind of electrical attraction held the atoms together.

Berzelius supposed that copper atoms and chlorine atoms combined because they had opposite electrical charges and so attracted each other. This theory was satisfactory and was, in fact, a near approximation to the truth as long as it was applied only to acids, alkalis and salts: but it entirely broke down when applied to other types of compound—notably organic compounds. Here combination seemed to take place quite irrespective of electrical character and the partial success of Berzelius's theory could not be explained until the twentieth century.

Finally it must be remembered that the years 1800–50 established the technique of accurate chemical analysis, so that by the middle of the century, the succession of brilliant discoveries which ensued was made possible through the existence of much exact information from which deductions could be made.

THE PROGRESS OF ASTRONOMY FROM 1600–1850

The effect of the theory of Copernicus was but little felt during the sixteenth century. As we have seen, Tycho Brahe adopted a compromise between the Copernican and Ptolemaic theories, and only at the beginning of the seventeenth century did Galileo compel attention by his telescopic demonstrations. In the years between 1600 and 1850 the substantial outline of the universe as we picture it to-day, was built up. Before the work of Copernicus, and indeed for some time after, the universe was pictured as having the earth at its centre. Round this revolved and rolled in excentric and epicyclic motions spheres of crystalline material bearing with them

the sun and moon and five planets: outside all revolved a sphere bearing the fixed stars, all of which were supposed to be immutable and equidistant from the earth. Outside this was a celestial region of eternal bliss.

Contrast with this the views held in 1850. The sun was then known to be a star and not a star of the greatest size, and the earth to be one of the smaller planets revolving round it. The solar system was not believed to be stationary, but to be moving towards the constellation of Hercules. The stars were known to be exceedingly far away and the distance of a few of the nearest had been measured. Round the sun rotated in elliptical orbits eight major planets with numerous satellites, a number of minor planets or asteroids, several comets and swarms of meteorites. The whole universe was believed to be a flattened disc: conjectures had been made that nebulæ might be island-universes beyond the confines of our own, though little evidence for this was available. The laws of dynamics accounted for the motions of these bodies with great accuracy and any minute residual errors were ascribed to errors of observation and not to failure of these laws.

The view of 1850 differed from that of to-day chiefly in its lack of knowledge as to the history of the universe (a creation some 6000 years earlier was still credible), and in its ignorance of the nature of the heavenly bodies, for the spectroscope, by which we can discover from the light of the stars their composition, temperature and motions, had not been invented.

It is broadly true to say that the astronomers before 1600 contented themselves with the mathematical description of the apparent motions of heavenly bodies. From 1600 to 1850, the work of astronomy was to define the

real positions, and real motions of these: and to produce a theory, based on the law of Gravitation, to explain these motions and to some extent to discover their causes. Since 1850 Astronomy has been exercised chiefly as to the nature and history of the stars and on the consequences of the Theory of Relativity, which has provided a view of the universe closer to observed fact, if less easily intelligible, than the Newtonian.

The new discoveries made between 1600 and 1850 aroused but little theological odium, and the work of building up the new cosmic view proceeded smoothly and without the fulmination of religious controversy. The Ptolemaic view of the universe was, it is true, an official Catholic tenet, but after the seventeenth century little attention, even in Catholic countries, was paid to this ruling. In Protestant countries the religious life of 1600 to 1850 was centred very closely on the Bible and cared little for the Aristotelian theories of the Middle Ages or the interpretations of the Fathers. The Bible gives no official cosmology. The new Astronomy did not appear to conflict with a recent creation, or the belief in the deluge: it magnified the work of God and humbled that of man. Consequently it was the exception to hear of an irreligious astronomer before 1850.

KEPLER AND DESCARTES

The Copernican system of circular orbits was imperfect. Even the inaccurate observations of the time showed that it could not be reconciled with observation without introducing the Ptolemaic notion of epicycles and eccentrics. Tycho Brahe (1546–1601) greatly refined the

observational data, carrying out continuous observations accurate to about one minute of arc. Kepler (1571–1630) inherited Tycho Brahe's data and set himself to find a system of motion of the moon and planets which would explain these observations. Kepler was a man of his age, prone to indulge in the wildest speculations, and a firm believer in astrology. Yet he was a man of great intellectual rectitude: he devised system after system of motion based on circular orbits, but rejected each because it would not conform exactly to the observations. The idea that the circle, on account of its extreme perfection of symmetry, was necessarily the heavenly figure, appealed to the learned men of the seventeenth century no less than to the Greeks; it was with difficulty that Kepler brought himself to consider first an oval, then an ellipse having the sun at one focus. This he found to agree well with the orbit of Mars: he next studied the alteration of the speed of motion of the planet as it travelled along the elliptical path. His first laws were:

1. The planet describes an ellipse, the sun being at one focus.
2. The straight line joining the planet to the sun sweeps out equal areas in any two intervals of time.

In later years Kepler, who, like most of the men of that Platonick age, had a profound belief in the mystical significance of numbers, sought for a relation between the various measurements of the solar system: he discovered thus his third law:—

3. The squares of the times of revolution of any two planets (including the earth) about the sun are proportional to the cubes of their mean distance from the sun.

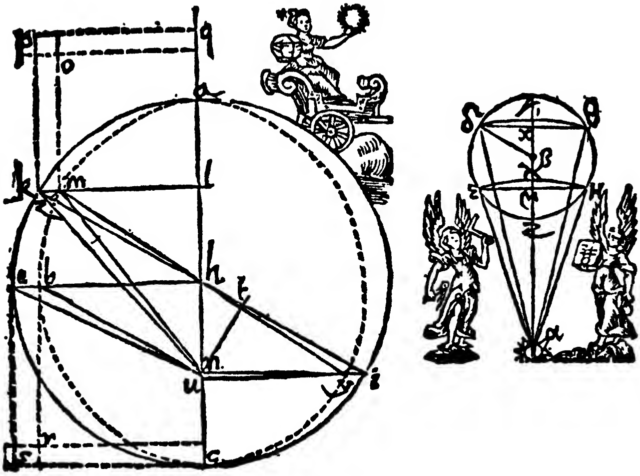


FIG. 25

Kepler's delineation of the elliptical orbit of Mars. Note the triumphal chariot. (From his *Astronomia Nova* 1609.)

The cause of such motions was, of course, obscure to Kepler, who inclined to think that the planets were guided by some occult agency—angels or genii. There are indications that he had some notion of a mutual action between bodies, a vague forerunner of the idea of gravitation which Newton was to develop.

Between the time of Kepler's work (*c.* 1620) and that of Newton (*c.* 1670) a good deal of progress was made in the discovery of new objects. Huygens much improved the telescope, in consequence of which the satellites of Saturn and its rings were discovered. He also constructed a pendulum-clock, the first accurate time-keeper. The distance of Mars was calculated by the aid of observations simultaneously made in Paris and Cayenne. From this the distance of the sun was calculated as 87,000,000 miles; the true value is about 92,900,000 miles.

In 1644 Descartes, mathematician and philosopher,

put forth his famous Theory of Vortices, by which he explained almost everything in nature, and notably the planetary motions. The theory was deduced *a priori* from metaphysical considerations. It was not supported by observation and proved on the whole to be a hindrance to the advance of knowledge. None the less, it attracted great attention, had at any rate the merit of provoking free discussion as to the cause of planetary motions. Descartes believed that the universe was completely full of material particles in contact. If a single particle moved, others were compelled to move and so to take its place. Thus, thought Descartes, any motion in such a universe would set up a series of whirlpools or *vortices* of

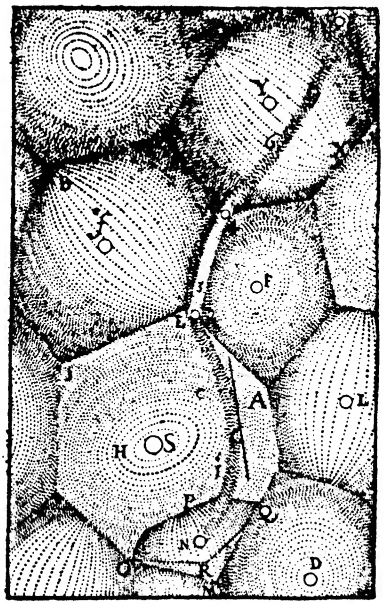


FIG. 26

The course of a heavenly body according to Descartes' theory of Vortices. (*Principia Philosophiae.* 1644.)

particles. The friction of the particles in each vortex would detach parts of the particles so producing (1) globular particles, which continued to rotate as a vortex and which may be thought of as analogous to the ether of space; and (2) finer dust which settled to the centre of the whirlpool and formed a star. The planets were thought to be former stars which had become encrusted with a third type of particles and whose vortices had been diminished by contact with other vortices; such bodies, he supposed, might be caught up by the sun's vortex and continue to be carried round therein.

The theory was attractive because of its simplicity: it was the first completely rational theory of the universe, nothing being presupposed except impact between particles. It seemed, indeed, more rational than the Newtonian view, for the "attraction" which the latter supposed seemed to be an occult and immaterial property.

The vortex theory completely dominated science for twenty years after its publication in 1644 and, until well into the eighteenth century, remained a formidable rival to the Newtonian view.

NEWTON AND GRAVITATION

The great astronomical event of the late seventeenth century was Newton's discovery of the laws of gravitation. To give a popular account of Newton's work is far from easy, for most of it is only to be described in mathematical terms. His achievement in Mathematics and Physics is gigantic; in Astronomy he did no less than to establish the system of the world. The notion of attraction between two bodies had been vaguely envisaged and confusedly

compared to magnetism, but no clear-cut ideas had as yet emerged. Newton first worked on the notion of gravitation about 1665 when he was only 24. He was apparently led to the idea by the realisation that any body whirled in a circular orbit tends to continue in a straight line and can only be made to continue its circular motion if given an acceleration towards the centre. A stone whirled on the end of a string is only kept in its circular orbit by the pull of the string. Now the planets move approximately in a circular orbit; some force must then act between them and the sun about which they rotate. This force, he supposed, to be an attraction, which existed between all particles of matter. This was a bold step, for the idea of action at a distance was so novel that Huygens supposed it absurd and unworthy of investigation. Newton then showed that if this attractive force varied as the square of the distance between the bodies attracted to each other, Kepler's laws of motion of the planets would necessarily follow. Newton was not at first able to verify his hypothesis by calculating therefrom the motions of the earth and moon, for many of the necessary data were unknown; he laid the work aside and devoted himself for some years to optics and mathematics. The stimulus which led him to resume the work was Halley's rediscovery of the connection between Kepler's third law (p. 185) and an attraction following the inverse square law. Halley consulted Newton and found that the latter had already worked it out. Under Halley's influence Newton wrote his great treatise the *Philosophiae Naturalis Principia Mathematica,* which deals with the motion of bodies and the application of the laws of motion to the solar system. Such fundamental ideas as those of mass, force, action and reaction, appear clearly defined for the

first time in the earlier part of the Principia. He established the principle that *Every particle of matter attracts every other particle with a force proportional to the mass of each and inversely proportional to the square of the distance between them.*

The problem of applying this law to the calculation of the orbits of the solar system was difficult, because in calculating the orbit, let us say of Mars, account has to be taken not only of the sun's attraction for Mars, but of the attractions of Earth, Jupiter and other planets. The perfection of mathematical methods of taking into account these numerous attractions was largely beyond the power even of the great mind of Newton; a century of work, indeed, was required before it could be done. None the less Newton showed that the orbit of the moon could be fairly adequately explained as the result of the combined attractions of earth and sun.

The work of Newton had, indeed, created a new view of the universe. The mechanics by which the motion of terrestrial things could be predicted was shown to apply to the celestial realms: the course of the moon was governed by the same forces as directed a cannon-ball. The Newtonian universe was founded on an absolute Space and Time, independent of our sense-perceptions of duration and extension. Matter was considered to be atomic. For the first time it was believed that a sufficient extension of science would enable all natural phenomena to be explained in terms of forces acting upon particles—in terms, that is, of the conceptions of mass, length and time. No longer were bodies thought to possess hidden "proper natures" in virtue of which they behaved in their characteristic fashion; their behaviour was thought to be due to the effect of a few forces, such as gravity or

cohesion, acting upon them or their constituent atoms. This view of the universe readily fitted in with the materialistic world-view of the nineteenth century: Newton, however, took no such attitude. God, he thought, pervaded the whole universe: by existing always and everywhere He constituted absolute Time and Space. Newton, indeed, was deeply interested in what, to-day, we would call the occult, though at that time it seemed a rational field of study. He is said to have wished to learn Mathematics in order to study astrology: he also left a great quantity of writings on alchemy, which have not yet been well studied, and also a considerable commentary on the Apocalypse. It seems probable that Newton, more wise than the scientific man of to-day, regarded all phenomena, whether of the mind or of matter, as equally forming a part of the Whole and therefore as equally worthy of study and investigation.

It was some time before Newton's theories gained any general acceptance on the Continent, where the views of Descartes held the field. From about 1730 to 1830 a succession of great mathematicians, Euler, Clairault, D'Alembert, Lagrange, and Laplace, worked on the problem raised by Newton's Law of Gravitation, namely: *Given a number of heavy bodies moving under the influence of their mutual gravitation, what will be their paths?*

The problem proved exceedingly difficult; even when the number of mutually gravitating bodies is limited to three, it cannot be given a general solution. However, certain cases of the problem can be solved and in all cases close approximations can be made. The work of the century between 1730 and 1830 resulted in an almost complete system of calculation of the orbits of planets and satellites on the basis of Newton's laws.

The laws of gravitation enabled the mass of the sun, planets and earth to be calculated, with the result that by the beginning of the nineteenth century the dimensions of the solar system, and the velocities and masses of the bodies composing it were clearly known. Man had learnt the nature of his own corner of the universe.

While the motions of the solar system were being worked out, other advances went on. Observations were steadily made more accurate till the error of one minute of arc in Tycho's work gave place to errors of three or four seconds of arc only. Many refinements were added to the observations of the positions of stars. Comets, which before Tycho Brahe's time were thought to be vaporous exhalations in the earth's atmosphere, were shown in many cases to return periodically, moving in elongated ellipses about the sun. Halley's computation of the periodic return of the comet named after him went far to quell the fear of comets as being portents of evil.

In the later part of the eighteenth century flourished F. W. Herschel (1738–1822), one of the greatest of astronomical observers. He constructed more efficient telescopes than any before him and systematically and continually observed the heavens. He studied nebulæ—which had been previously noticed—and advanced the view, later rejected but now proven, that some of these are island-universes. Double stars forming rotating systems were his discovery. But greatest of all was the advent of a new planet now called Uranus. The sun, moon and five planets had existed since the earliest records: the satellites, after the first excitement of their discovery by Galileo and others, were not felt to be a serious disturbance to this plan. A new major planet seemed to be one of the great events of history.

Herschel made some attempt to map out the form of the universe. He assumed as a rough approximation that the stars were at about equal distances from each other. A belt of densely sown stars, the Milky Way, seems to encircle the heavens while on either side of the plane of this belt, much fewer stars are seen. Herschel concluded that the universe was a flat disc, near the centre of which was the solar system. Looking towards the edge of the disc, vast numbers of stars would be in view and give the appearance of the Milky Way, while between the observers and the face of the disc there would be comparatively few. Herschel also detected a very small proper motion of a few of the stars; he deduced from a common element of all these motions that the sun with its attendant planets was moving towards the constellation of Hercules.

The discovery of Uranus was followed by that of a number of very small planets occupying the space between Mars and Jupiter. Ceres was discovered in 1801, and new asteroids have been continually discovered from that time till the present: some 2000 of these have now been observed.

In the early nineteenth century Bessel (1784–1846) made a great advance by measuring the distance of a star. The stars are so distant that when observed from opposite sides of the earth's orbit, even the nearest seems to shift through only some $\frac{3}{4}$ sec. of arc. Bessel was able to measure this minute shift and deduced therefrom that the nearest stars were more than 250,000 times as distant as the sun, itself some ninety million miles from the earth. The gigantic scale of the stellar universe was revealed, and for the first time the stars became something more to the astronomer than immovable points of light. The spate of new knowledge about the stars began, however, only after the spectroscope was invented.

The discovery of the planet Neptune by Leverrier and Adams independently was a triumph of the gravitational Astronomy which had evolved from the discoveries of Newton. The planet Uranus showed irregularities in its motion which could not be explained by the disturbances due to the attraction of Jupiter and Saturn. Both Adams and Leverrier were able correctly to calculate from these disturbances the place in the sky where the disturbing body should be sought. They both asked observers to look for the new planet: Leverrier's friend, Galle, duly found the body sought for, which was named Neptune. The year 1846 then saw the discovery of what was believed for many years to be the last major member of the solar system. Yet in 1930 the planet Pluto, far more distant than Neptune, was discovered: we should be loth to assert that this is the outermost member of our planetary family.

Laplace (1749–1827), who also was one of the great astronomer-mathematicians, is noteworthy as having departed from the tacit assumption that a Deity created the universe as it is to-day and as having advanced a theory of the manner in which the solar system might have been formed.

The philosophers from the Greeks to Kant had put forward their theories of the evolution of the universe. Lucretius started from a hail of downward-falling atoms, Descartes from his universe of close-packed particles, Kant from a vast cloud of evenly spaced particles. All these were arm-chair theories. Laplace came nearer to a scientific explanation of the evolution of a solar system in that he used well-known mechanical principles to explain *how* it might have occurred, though he did not attain to the exactness of mathematical demonstration.

Laplace started from a sun surrounded by a vast slowly-rotating nebula of glowing gas extending beyond the confines of the present solar system. As this nebula cooled, it contracted: this, he showed, must result in a speeding-up of the rotation. This acceleration, he supposed, caused a rotation so rapid that the central body could no longer retain its outermost layer, which was thrown off as a rotating ring of glowing vapour. A succession of such rings were thus formed, each of which then broke up and re-united to a single body, the planet. The planet threw off satellites in the same way. The theory was supported by the facts, very improbable in any chance distribution of planets, that the planetary orbits lie nearly in one plane and that all the planets and almost all the satellites rotate and revolve in the same direction. Saturn's rings seemed to confirm the notion, and the four asteroids known to Laplace were thought to be fragments of a nebulous ring which had failed to coalesce. Further knowledge has shown that Laplace's theory is not tenable, although it approaches more nearly than any earlier ideas to our present theories, which may not be correct, but at any rate have good mathematical and physical evidence to support them.

BIOLOGY, 1500–1850

The period between 1500 and 1850 saw the building up of ordered and substantially accurate biological knowledge.

During this time the main features of the anatomy of man, of the well-known types of animals, and also of plants were worked out. A great number of species were described and named, and a rational system of classifying

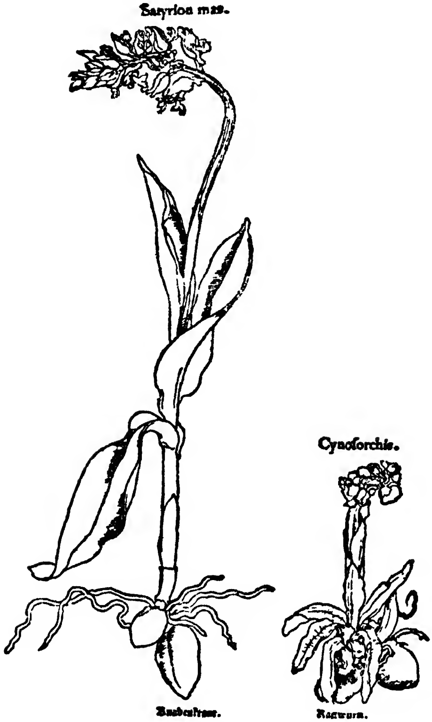


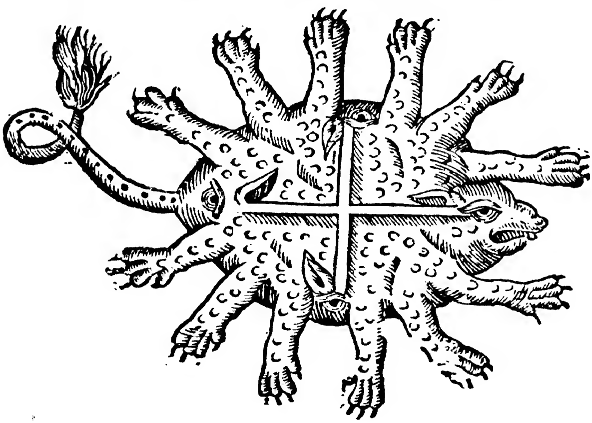
FIG. 27
An orchis from Otto Brunfels' herbal.
(*Herbarum vivæ eicones*. 1530–40)

them was evolved. Some of the less difficult problems of physiology were solved, notably those of the circulation of the blood and the nature of respiration. But even in 1850 biological knowledge remained largely descriptive and the great unifying discoveries which have begun to make rational the study of living things are the work of the last eighty years.

Before 1500, Aristotle was the only biologist—using the term to signify one who attempted a general study of the living world. The study of Anatomy and of Botany was a part of medical learning, and so remained alive

Figure d'vne beste monstrueuse, laquelle ne vit que de vent, dite Haiit.

Figure d'vn animal fort monstrueux, naissant en Afrique.



Mais qui est celuy qui ne s'esmerueillera grandement de contempler cette beste, ayant tant d'yeux, oreilles & pieds, & chacun faire son office ? où peuuent estre les instrumens dediez à telles operations ? Veritablement quant à moy i'y perds mon esprit, & ne sçaurois autre chose dire, fors que nature s'y est ioüée, pour faire admirer la grandeur de ses œuures.

FIG. 28

Above a sloth (?) and below *un animal fort monstrueux* from Ambroise Paré's work on monsters (1573). (From *Les Oeuvres d'Ambroise Paré*. Tenth ed. 1641.)

throughout the Middle Ages; the study of Zoology degenerated into the recounting of stories about beasts.

The first signs of biological revival were seen in the attempt to produce herbals illustrated from nature. Brunfels, Bock and Fuchs in Germany between 1530 and 1542 produced descriptions and illustrations of plants which were an enormous advance on those of the Middle Ages. Bock even makes some attempt to classify plants, a task which was taken up again in the seventeenth century.

A landmark in the description of animals was the great work of Conrad Gesner (1516–65) which in four magnificently illustrated volumes collects all that was known of the animal kingdom. In the descriptions of animals given in the sixteenth century, there is still much uncertainty about those which inhabit distant lands. None the less wherever it was possible careful drawings were made from nature. An uncritical attitude still existed and no monster was too strange to receive serious consideration. In the sixteenth century little account was taken of the animals other than vertebrates. Mammals, reptiles, birds and fishes were well described, but insects, worms and other lowly creatures had hardly been noticed.

One of the chief events in the history of Biology was the discovery of the microscope. The first compound microscope was constructed about 1590; Galileo before 1610 made crude microscopes and studied insects therewith. Rapid improvements were soon made. After 1660 systematic use of the microscope in scanning the anatomy of plants and animals became common. This work drew attention to the unsuspected marvels of the insect world and prompted a wonderful series of studies of insects. Consequently it was soon realised that insects, worms and molluscs had an anatomy almost as complex

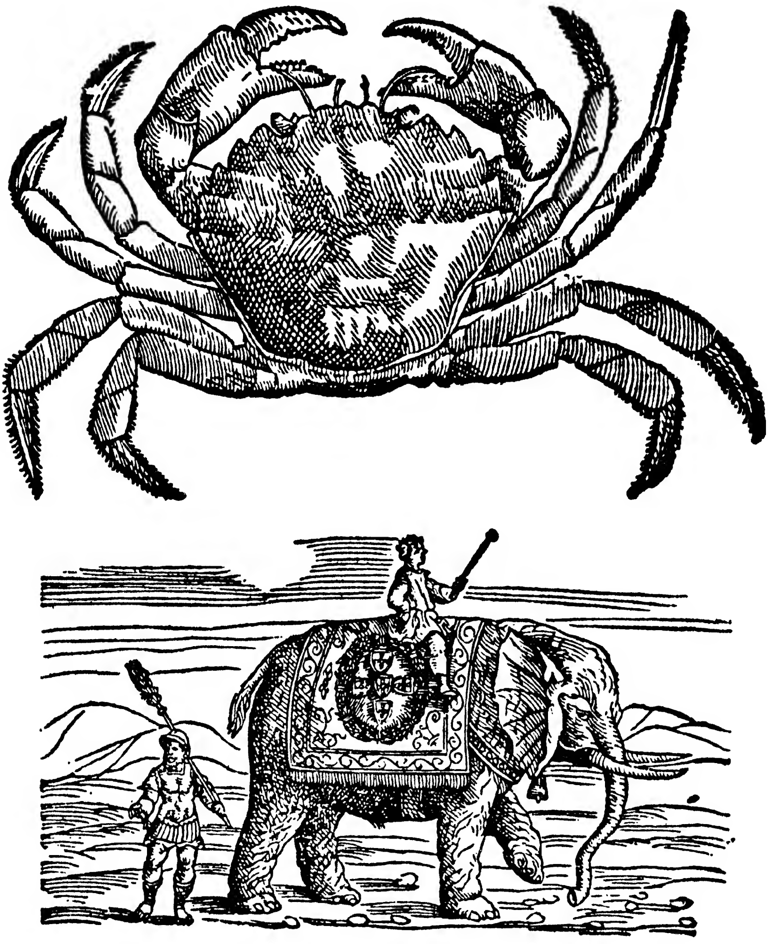


FIG. 29
Illustration of a crab and an elephant in an early sixteenth-century commentary on Dioscorides, showing the difference between drawings from life and from hearsay.

as, but quite different from that of vertebrates; moreover the existence of a wholly new world of invisible microscopic animalcules fascinated the learned.

Discoveries of new plants and animals, especially in the Americas and the Far East, were rapid, and made

ever more urgent the need for a systematic nomenclature and classification of living things.

THE CLASSIFICATION OF LIVING ORGANISMS

John Ray (1627–1705) produced the first systematic natural history. He defined a "species" as one which exactly reproduces its peculiarities from generation to generation—a fair approximation to the modern view. His groups, however, are often artificial, and cannot be compared with those of Linnaeus.

Carl Linnaeus (1707–78) was the founder of modern biological classification. He developed a systematic method of describing each organism, and evolved a system to include every known living creature. He invented the binary system of nomenclature. Each genus was represented by a single term; thus, for example, a number of plants having an obvious resemblance to each other both in form and structure were grouped as the genus *Tulipa*. Each species was characterised by a second term, thus the species of the above genus which had a "somewhat nodding flower and lanceolate leaves" was characterised as *Sylvestris*, and generally known as *Tulipa Sylvestris*.

These genera he grouped into larger Orders, which were themselves grouped into yet larger Classes, which made up the kingdoms of animals and plants. His classification of plants was based on the reproductive organs, stamens and pistils and proved much superior to his classification of animals, in which, for example, all forms other than vertebrates and insects are lumped together as Vermes or Worms. Linnaeus believed that

species were completely fixed and had remained unaltered since the Creation.

Buffon (1707–88), wrote a work, *Histoire Naturelle*, which had great influence. In this he takes a broad view of the whole world as subject to mechanical laws of nature, and at the same time describes individual phenomena, such as the habits of animals, with brilliant and vivid detail.

During the early nineteenth century the study of comparative anatomy developed and not only the form, but also the structure of animals, was closely studied. Cuvier (1769–1832) made it his task to try and build up a sound classification, based on a systematic study of comparative anatomy. He divided the Animal Kingdom into four main groups:

Vertebrata.	(Animals with backbones.)
Mollusca.	(Mollusca, e.g., snails, cuttlefishes.)
Articulata.	(Insects, annelids, etc.)
Radiata.	(Star-fish, sea-urchins, sea-anemones, etc.)

These four classes he considered to be wholly unrelated to each other.

Cuvier founded the systematic study of fossil remains, about which many curious opinions had been expressed. Some thought that the fossil sea-shells, often found in the rocks remote from the sea, were relics of the Deluge: others believed they were not the remains of creatures which had once lived, but that the formative virtue which issued from the stars and planets, caused them to grow in the rocks, much as crystals are formed from a solution. Cuvier made it clear to the world in general that fossils were the remains of living organisms, and of such organisms, moreover, as are not to be found alive in the present age. Their extinction he supposed to be the result of volcanic upheavals of such magnitude as to destroy

all living creatures. Cuvier does not theorise on the subject of the creation of species, but was opposed to the idea of any species having been formed from another.

Lamarck (1744–1829) was also a great systematist. He divided the invertebrates into ten classes, which are very nearly the same as those now adopted. But apart from this specialised work we remember him as an exponent of the notion of the evolution of species. He believed that animals modified themselves by a kind of striving towards more advantageous conditions (p. 278). Consequently, like Aristotle, he believed that the animal kingdom could be expressed as a series or ladder stretching from the lowest form to the highest. The notion of the evolution of species was in the air throughout the years between 1800 and 1850, but remained merely an interesting speculation until 1851 when Darwin gave it adequate expression and experimental support.

We may note then, as the first result of the work of the period 1500–1850, the accurate description and examination of a large part of the living, and a small part of the extinct species, of animals and plants, and their classification into an ordered system, the significance of which was the task of the succeeding years to explain.

THE PROGRESS OF PHYSIOLOGY, 1600–1850

The understanding of the intimate nature of the life-process naturally lagged far behind the descriptive sciences of natural history and anatomy. Progress was made, however, towards explaining the mechanical operations of the body such as the circulation of the blood and the mechanical action by which the contractions of muscle moved the joints. The dependence of life upon air was

proved in the seventeenth century, but chemistry was in so undeveloped a state that it was not until near the end of the eighteenth century that the function of respiration was understood to be combination with oxygen. The elucidation of the chemistry of the life-process could hardly be attempted before the last half of the nineteenth century, and nine-tenths of the chemistry of the life-process remains obscure at the present day.

A lack of understanding does not hinder the building of theories, and, indeed, it is hard for the man of speculative mind to avoid building an explanation of life, though it be on a frail foundation.

Descartes held the belief that the life-process was wholly determined by natural law, that animals were automata without souls, and that man alone possessed a rational soul, which influenced his body through one gateway only, that of the pineal gland in the brain (an organ of which the function is still obscure). This view was in sharp contrast to the Animism of Stahl, who believed that the soul regulated every part of the life-spirit, and to the views of the Vitalists, who believed that there was a Life-force which was capable of performing in the body processes which could not occur outside it. The views of the Vitalists were later weakened by the laboratory synthesis of compounds which were believed to be characteristic of living matter: but vitalism survives to-day in a less crude form. Vitalism, in the middle of the nineteenth century, gave way to Materialism, which is the belief that no entity takes part in the life-process, other than the atoms, molecules and forces, which constitute and influence non-living matter.

The increased understanding of reproduction gained in the seventeenth, eighteenth and nineteenth centuries, had

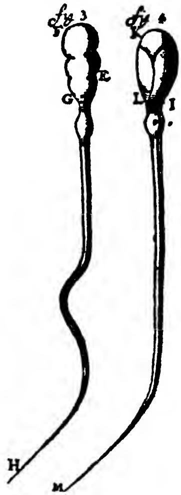


FIG. 30

Spermatozoa, observed by Leeuwenhoek with a simple lens. (From his *Opera Omnia*. Leyden. 1715–22.)

much influence on the world's thought. The development of the chick in the egg and of the *foetus in utero* had been studied even before the time of Aristotle, but no understanding of the process of fertilisation could be reached without the aid of the microscope.

Leeuwenhoek examined semen with the microscope and saw in it actively moving spermatozoa. He published this in 1679. The notion that the male contributed living organisms to the act of fertilisation was of vast interest. Leeuwenhoek even supposed he could discern the lineaments of men and women in these microscopic animalcules. He saw, in the frog, the association of spermatozoa with eggs, but he believed that only the sperm was living, and that the egg was merely a place of nourishment for it.

Controversy on this matter followed for a long time and it was only from the year 1847 on, that the mechanism of fertilisation of one egg by one sperm was observed and understood. The development of the embryo in its later stages was readily studied by dissection and by 1850 had been very well worked out.

A beginning was made in the study of the life-processes of plants. The first problem to be attacked was that of their sexual processes. Camerarius between 1691 and 1694 showed that pollen was indispensable to the development of a seed capable of germination. Between 1761 and 1766 Koelreuter showed that the pollen transmitted the character of the plant from which it came; he carried out hybridisation by placing pollen from one variety of plant on the pistils of another. Sprengel, at the end of the eighteenth century, explained the part which insects play in pollination. The mechanism by which pollen fertilised the ovum was much more difficult to observe. The growth of the pollen-tube down towards the ovum was discovered in 1823, but it was not till 1850 that Hofmeister showed that a fusion of male and female cells took place in plants and that their fertilisation was truly analogous to that of animals.

A beginning was also made in the study of the nutrition and respiration of plants. Van Helmont (p. 166) grew a willow-tree in a pot and showed that the loss of weight of the earth was inconsiderable beside the gain of weight of the tree: consequently the substance of the plant could not come from the earth. He naturally concluded that the plant had been formed from the water with which it had been supplied. Stephen Hales about 1727 showed that plants could not live without a supply of air. Priestley in 1771 showed that the alteration made in the air by the

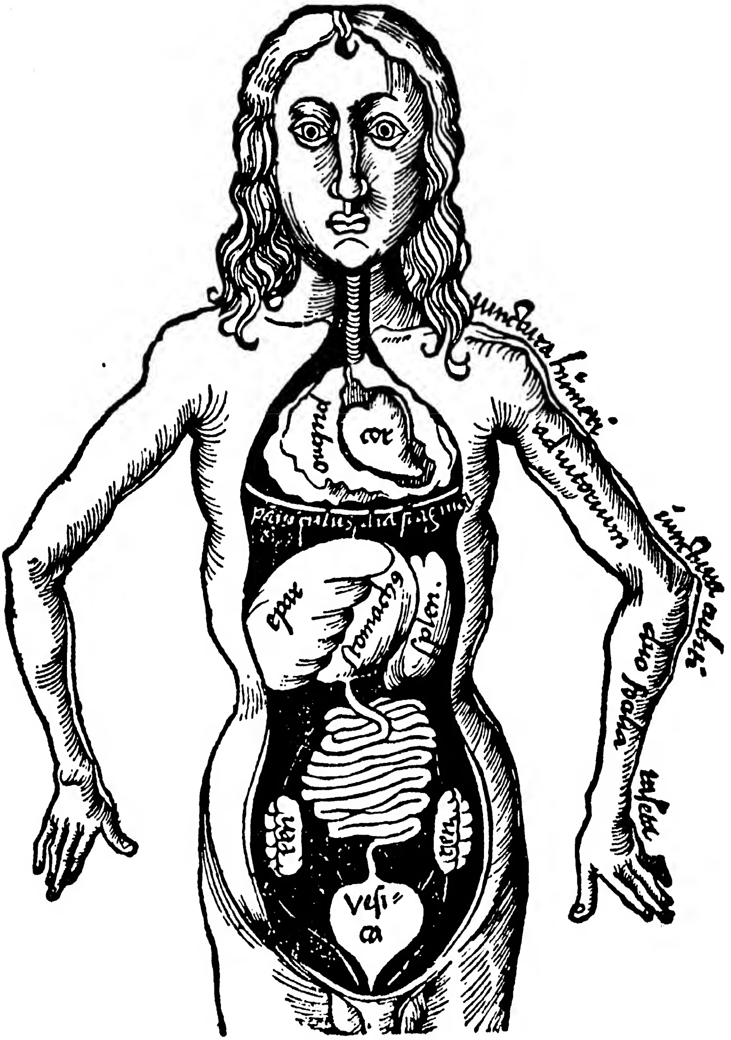


FIG. 31

The mediæval notion of anatomy. (*Margarita Philosophica.* Reisch, 1508.) Contrast this with Fig. 32, only forty years later in date. The chief organs shown are *pulmo* (lung), *cor* (heart), *epar* (liver), *stomachus* (stomach), *splen* (spleen), *ren* (kidney), *vesica* (bladder).

breathing of animals or by combustion was restored by green plants: Ingen-Housz in 1779 showed that the carbon of plants comes from the carbon dioxide in the atmosphere, and that, while living plants give off carbon dioxide continuously, oxygen is given off only by their green parts when exposed to sunlight. Senebier before this date had pointed out the influence of light, which however he regarded as a material substance, not as energy. De Saussure in 1804 showed that plants obtained their nitrogen content from the soil and not from the air; he also showed that plants required mineral constituents derived from the soil.

HUMAN ANATOMY AND PHYSIOLOGY, 1500–1850

Medicine and the attendant sciences of human Anatomy and Physiology received far more attention than general Biology.

In the year 1500 Medicine and Surgery had not appreciably advanced beyond the level of the time of the Greeks and Romans. By the year 1850 these sciences had taken on a very different guise, but were yet utterly unlike the Medicine and Surgery of to-day. The pillars of modern therapeutics are the bacterial, protozoal and virus origin of disease; the curative use of Surgery, rendered possible by anaesthetics and the aseptic technique; and the recognition of malignant disease by examination of tissue-cells. The greater part of these principles came to light only after 1860.

The first step in the building of modern Medicine was to gain knowledge of Anatomy and Physiology—to find out how the body is made and how it works. The former task was largely completed by 1850, the latter is as yet fragmentary.

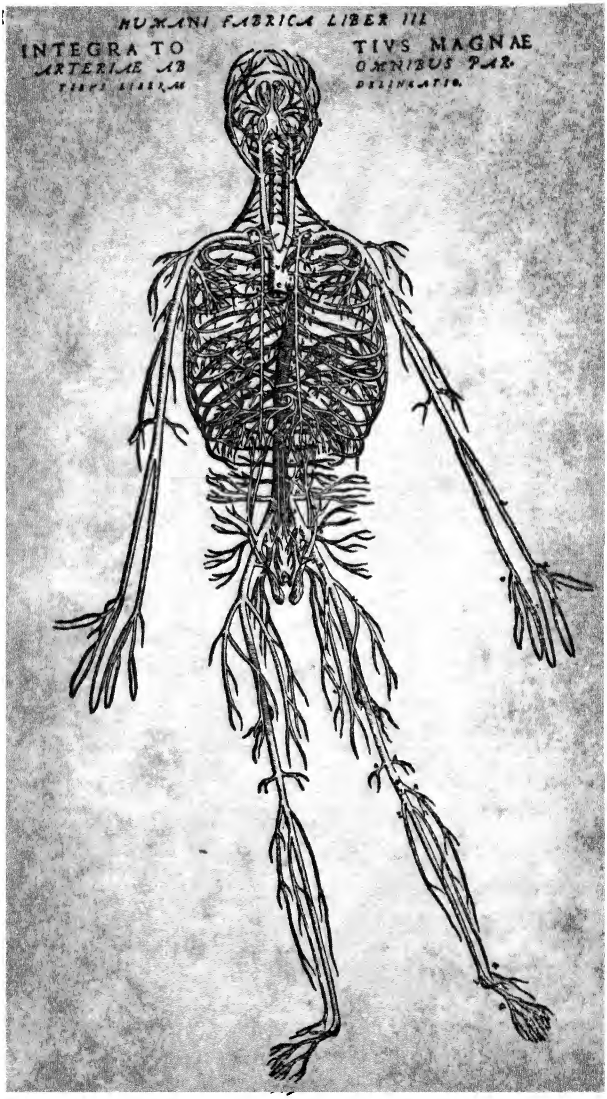


FIG. 32

The arteries from Vesalius' *Corporis Humani Fabrica.* (1543.) Contrast with Fig. 31.

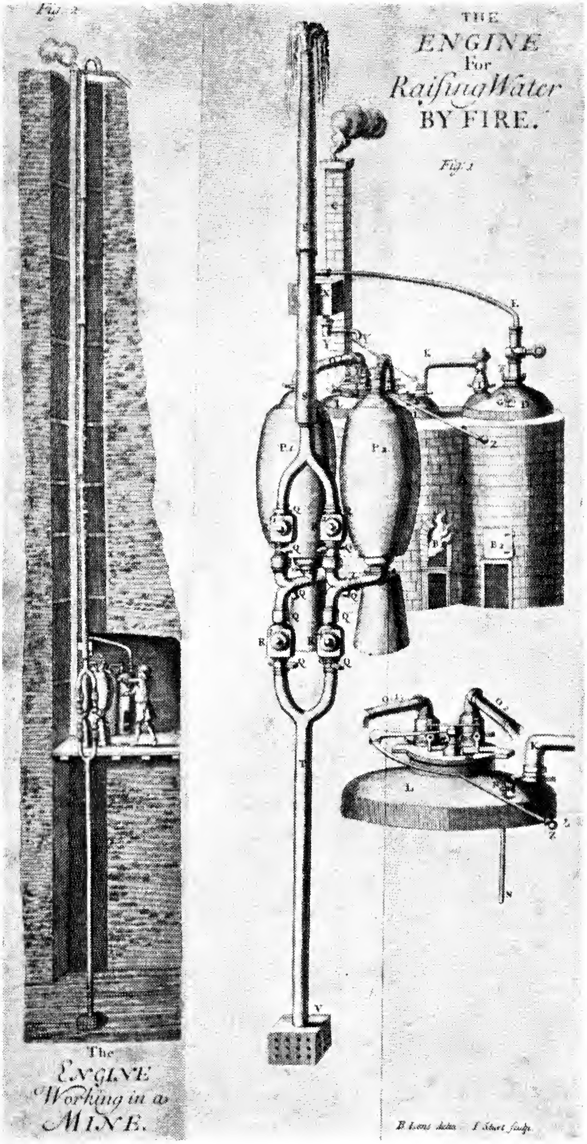


PLATE XII

The Savery engine. Steam is generated in the boiler L and displaces water alternately from the receptacles P1, P2. On condensation of the steam these refill with the water to be pumped. The boiler D provides hot water for refilling the boiler L. (From Thomas Savery. *The Miner's Friend.*

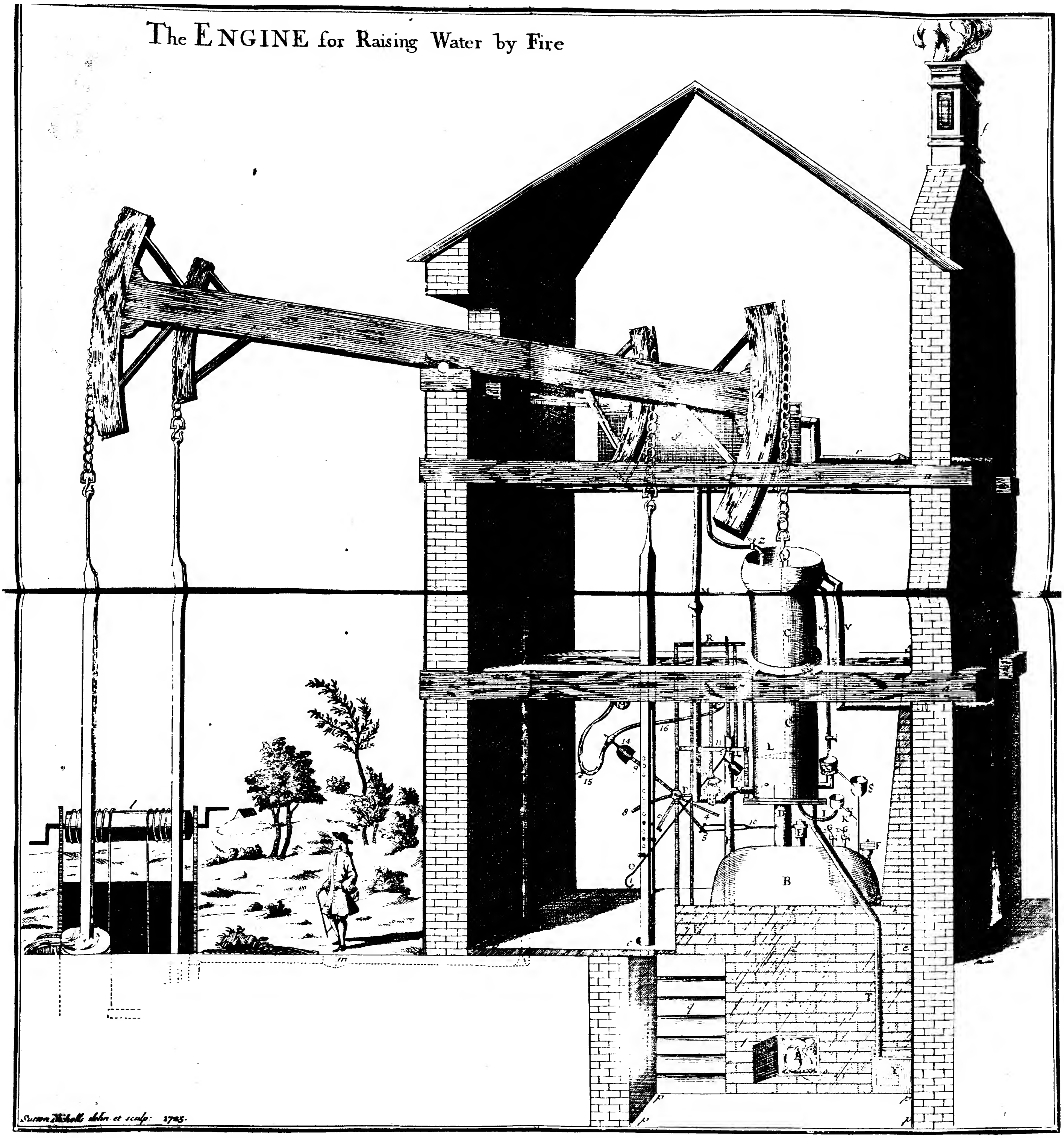


Plate XIII

The Newcomen Engine. (*c.* 1725.)

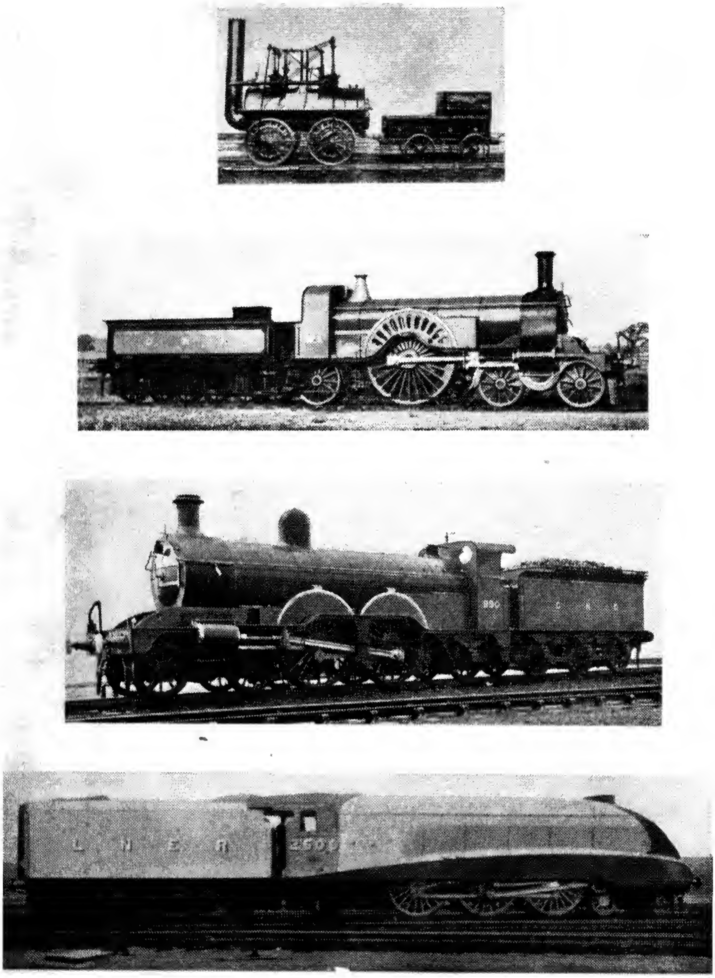


Plate XIV

The Evolution of the Locomotive. (1) 'Locomotive No. 1,' built by Geo. Stephenson for the Stockton and Darlington Railway in 1825. (2) The first 'Stirling Single,' 1867. (3) 'Henry Oakley,' the first of the Atlantic Class, 1898. (4) The 'Silver Link,' streamlined Pacific type, 1935. Approximately to scale. (Photographs kindly supplied by L.N.E.R.)

Leonardo da Vinci (p. 128) was the first scientific anatomist, but his work remained unknown. Very little later Andreas Vesalius (1515–64) revolted against the slavish adherence of anatomists to Galen and Aristotle. His many dissections of the human body led him more and more to distrust these authorities. His *Fabric of the Human Body*, published in 1543, was a substantially correct description of the structure of the body in so far as it can be elucidated without the microscope. The study of anatomy proceeded smoothly through the sixteenth, seventeenth and eighteenth centuries. Details were filled in and better and clearer drawings made. A great advance in technique was made by Ruysch (1638–1731) who invented the practice of injecting into the vessels an opaque fluid medium which solidified on cooling, thus rendering very clearly visible the course of arteries, veins and other vessels. The microscope gave proof of the existence of the capillaries and threw some light on the structure of muscle, bone and other tissues, though this was not made fully clear until the cell-theory was developed in the eighteen-forties.

The knowledge of the period was quite inadequate to allow anyone to frame a working theory of the mode of action of the body: none the less, such theories were framed. The iatrochemists regarded the body as a chemical machine, but had no chemistry fit to treat of its operation; the iatrophysicists regarded the body as a mechanical instrument. The latter were fairly successful in explaining the body's cruder activities; the motions of the limbs and the pumping of the heart were explicable on mechanical principles, but the theory was stretched too far and became fruitless.

The greatest physiological discoveries of the period

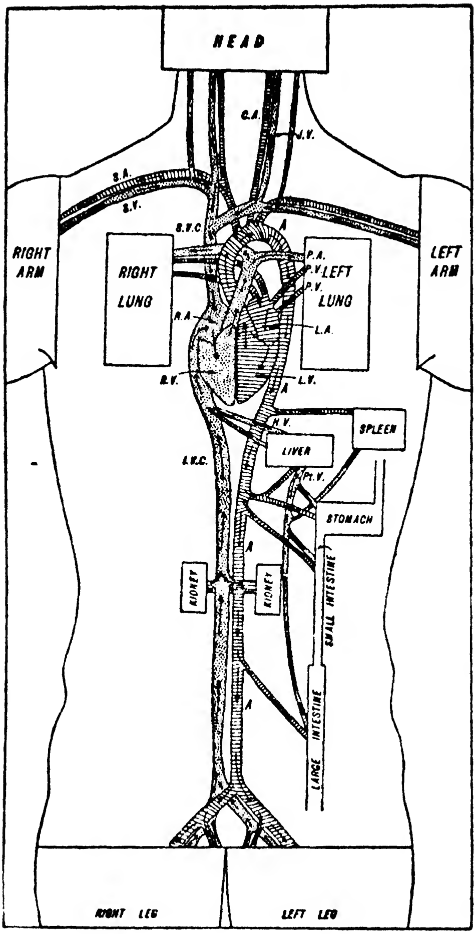


FIG. 33

Diagram illustrating circulations of the blood. (Arteries shaded by lines, veins by dots.) P.V., pulmonary vein. L.V., left ventricle.

were those of the circulation of the blood, and of the nature of respiration. The name of Harvey is deservedly remembered in connection with the circulation of the blood.

Erasistratus (*c.* 280 B.C.) believed that the arteries transmitted air; that in fact, air entered the body *via* the windpipe, lungs, pulmonary vein, left ventricle of heart, arteries and tissues. The veins alone, he supposed, contained blood and were a system entirely separate from the arteries.

Galen proved (p. 45) that living arteries contained blood. He supposed that the air which passed in and out of the lungs had the function of cooling the blood. Until the discovery of oxygen (1774) there was no reason to believe that air had any other function in the bodily economy. Galen supposed the arteries and veins to be two almost separate systems which had some small degree of communication through pores in the septum which divides the left ventricle of the heart from the right. These pores were the weakest point in Galen's account, and Vesalius declared them to be absent, as indeed they are. Galen supposed that the arteries contained "spirituous" blood, the life-spirit of which lodged in the left ventricle: the veins contained a darker and less spirituous venous blood.

In the period between 1500 and the work of Harvey (published in 1628) it had become known, though by no means generally, that blood passed from the right side of the heart to the left *via* the lungs, and that the blood travelled in the veins *towards* the heart. Harvey was the first to grasp the idea of a closed circulation. He saw that the valves of the veins could allow blood to pass only *towards* the heart. Consequently the flow of blood could only be in one direction. He showed that the quantity of blood transmitted by the heart within an hour greatly exceeded the weight of the whole body. It followed that the same blood must be passing through the heart con-

tinuously in the same direction—in a word—circulating. Harvey could not demonstrate the whole course of the blood, for the arteries subdivide to microscopic capillaries which reunite to form veins, but Malpighi in 1661, with the aid of the newly-discovered microscope, showed the capillary circulation in the lung of a frog and completed the evidence for the circulation of the blood. Stephen Hales in 1733 published some very interesting researches on blood pressure: by connecting a glass tube to an artery of a horse he showed that the blood rose in it to a height of several feet.

The problem of respiration proved even harder to solve than that of the circulation of the blood. In the early part of the seventeenth century the traditional views were still held; namely, that the object of the air drawn into the lungs was to regulate and cool the innate heat of the fire which inhabited the heart and was the source of the body's warmth. This air reached the heart *via* the pulmonary vein and was used to generate the "vital spirits which the heart pumped through the arteries to all parts of the body. The "fuliginous vapours" produced by the fire in the heart returned *via* the pulmonary vein to the lungs.

Borelli, who was of the school who believed the body to be a physical mechanism, rejected this view and supposed, equally erroneously, that the movement of the chest and air-vessels served to mix the parts of the blood very intimately. The work of Boyle, Hooke and Mayow in the second half of the seventeenth century came near to reaching the true facts. Boyle showed that when animals were placed in the receiver of an air-pump and the air was withdrawn, they very soon died. Hooke showed that the motion of the chest-wall was not essential, for by forcing air through the motionless lungs

of an animal its life could be maintained. Lower, about 1680, proved that air turned the dark venous blood to the colour of the bright red arterial blood and that the dark blood actually absorbed air. Mayow clearly showed that the same constituent of air as is used up by a burning candle is likewise used up by a breathing animal: he concluded that air actually entered the blood and that "combustion" took place throughout the body.

During the period of the phlogiston theory this work was neglected, and little or no progress was made. The general view in this period was that the motion of the blood generated heat mechanically by friction.

Priestley in the seventeen-seventies investigated respiration. He proved that green plants could restore the air which animals had vitiated by breathing. Priestley was a confirmed phlogistonist; he came, however, to an explanation of respiration in terms of phlogiston which was not far from the truth. Animals he supposed imbibe phlogiston with their food and expel it by their lungs. This in modern terminology would mean that animals took in food which underwent combustion in their bodies and that the products of this combustion were expelled *via* the lungs. The true explanation was given by Lavoisier who showed that oxygen was the substance taken up in respiration while carbon dioxide was given out. He rightly attributed animal heat to the combustion of carbon compounds in the body. Unfortunately he supposed, on very slight evidence, that a special "hydrocarbonous fluid" was secreted into the lungs and there underwent combustion. There were those who dissented from his views, but not until about 1837 was it proved that the oxygen was carried from the lungs throughout the body and that the "combustion" took place throughout the tissues.

SURGERY, 1500–1850

The progress of Surgery was up to a point rapid. As Anatomy progressed, so the boldness and skill of the surgeon followed it. Great advances were due to Ambroïse Paré (1510–1590) who practised for many years as an army surgeon and introduced two most important principles in the treatment of wounds. There had been handed down from the Greeks a maxim that what the knife could not aid could be cured by fire. Gunshot-wounds were, in the fifteenth and sixteenth centuries, considered to be poisoned burns and the standard treatment for them was the application of boiling oil. Paré, on one occasion, ran short of this medicament, and found that the wounded men who were not treated with it did better than those who had been duly scalded, and—here is the mark of genius—discarded the traditional treatment. The remedy for severe bleeding was the cautery: thus in an amputation, a hot-iron was applied to the stump to coagulate the blood. Paré reintroduced the tying of blood-vessels which had been in disuse since the first century A.D. He also practised the formation of proper flaps to cover the ends of amputation stumps. His surgical works are clear and practical: they are perhaps somewhat marred by his high opinion of his own work and by his rather credulous acceptance of wonderful tales. The absence of anaesthetics tended to restrict the use of surgery to the repair of wounds and to the gravest emergencies: moreover, the lack of understanding of the nature of the infection of wounds by bacterial contamination made its mortality high and recoveries slow. None the less even in the period of 1500–1850 surgeons

operated successfully for the cure of cataract, stone in the bladder, aneurysm and hernia. Amputations had been performed from early times, but were greatly improved by Paré's reintroduction of the tying of arteries and of the formation of proper flaps. Plastic Surgery was early developed, and even in the sixteenth century Tagliocozzi was able to renew noses lost through the ravages of syphilis.

It is true that the surgery of 1850 shows a great advance over that of 1600. The surgeon of 1850 had far more anatomical knowledge, and had perfected a technique which allowed him to perform in a period of a minute or two operations which to-day take half an hour. His ideal was speed: that of the modern surgeon is care. But the surgeon of 1600 and of 1850 alike could do so little compared to the modern operator that the surgical progress of the period seems to us but small.

Obstetric practice benefited enormously by passing out of the hands of the midwife into those of the accoucheur. The technique for turning the foetus and the invention of the obstetric forceps belong to this period.

MEDICINE, 1500–1850

Medicine developed even more slowly than Surgery. The medicine of the seventeenth and eighteenth centuries suffered from an excess of theory. One school of physicians very naturally tried to use the new knowledge of chemistry and physics to frame theories of the body's working, a task for which it was, of course, wholly insufficient. In opposition to these men who would make the body a physico-chemical machine were the animists

and vitalists who regarded the body as the seat of the soul or life-force which guided its operations: to disorders of this spiritual entity were attributed diseases. None of these systems afforded a rational system of treatment but, as in the medicine of to-day, a solid residue of proved experience accumulated while theories came and went. So in the sixteenth, seventeenth and eighteenth centuries a steady improvement in treatment went on. Superstition was steadily discarded until by the end of the seventeenth century the use of Astrology and talismans had disappeared from regular practice, though it lingered in popular Medicine. New drugs of great value were brought from foreign lands. Opium, quinine, jalap, ipecacuanha, coca, are among these. The use of mercurials for syphilis, and of the saline purgatives, Epsom and Glauber salts, were advances derived from chemical progress. Cleanliness improved and more rational systems of nursing came into use. A dislike of dirt and stench began to develop, though before the nineteenth century the improvements in cleanliness were aesthetic rather than hygienic.

The experiments of Stephen Hales (*c.* 1737) showed the importance of fresh air. Ventilation became fashionable, and the idea that such diseases as gaol-fever might be due to the stench in the prison cells, often ventilated only by a grille in the door, led to the instalment of ventilating fans in many of them. So perhaps, sprang up the idea of the connection between dirt and disease—an idea which after 1850 revolutionised the civilised world.

One important medical discovery requires a further mention. Smallpox was a deadly scourge up to the eighteenth century. In 1718 the practice of inoculating children with matter from the pustules of a mild case of smallpox was introduced from Turkey by Lady Mary

Wortley Montagu. This practice induced a mild attack of the disease which caused little scarring and a very small mortality, but even this method was felt to be rather risky.

Edward Jenner, about 1770, heard that Gloucester folk believed that an attack of cow-pox was a protection against smallpox. In 1796 he infected a boy with cow-pox and proved that inoculation with smallpox would not take on him. In 1798 he published a work in which vaccination is described. In 1808 a national vaccine establishment was formed. The merits of vaccination have been a matter of controversy, but it is hard to doubt that where practised it has brought about the virtual extinction of smallpox.

But the chief medical progress of the period 1500–1850 lay in the description and recognition of diseases. Such men as Sydenham used their eyes upon their patients and described the complexes of symptoms characteristic of various diseases. Pathologists studied the changes in the structure and tissues which these diseases brought about. Thus, although no great progress was made towards the cure or prevention of disease, clear descriptions and consequent powers of diagnosis were developed.

The greatest part of the diseases now known were thus recognised; their rational treatment had for the most part to wait for the latter half of the nineteenth century.

TECHNOLOGY, 1500–1850

The reader cannot fail to be struck by the fact that the fundamental scientific discoveries of the years 1600–1800 made remarkably little impression on the life of the people. It is perhaps true to say that the habits of 1938 differ from

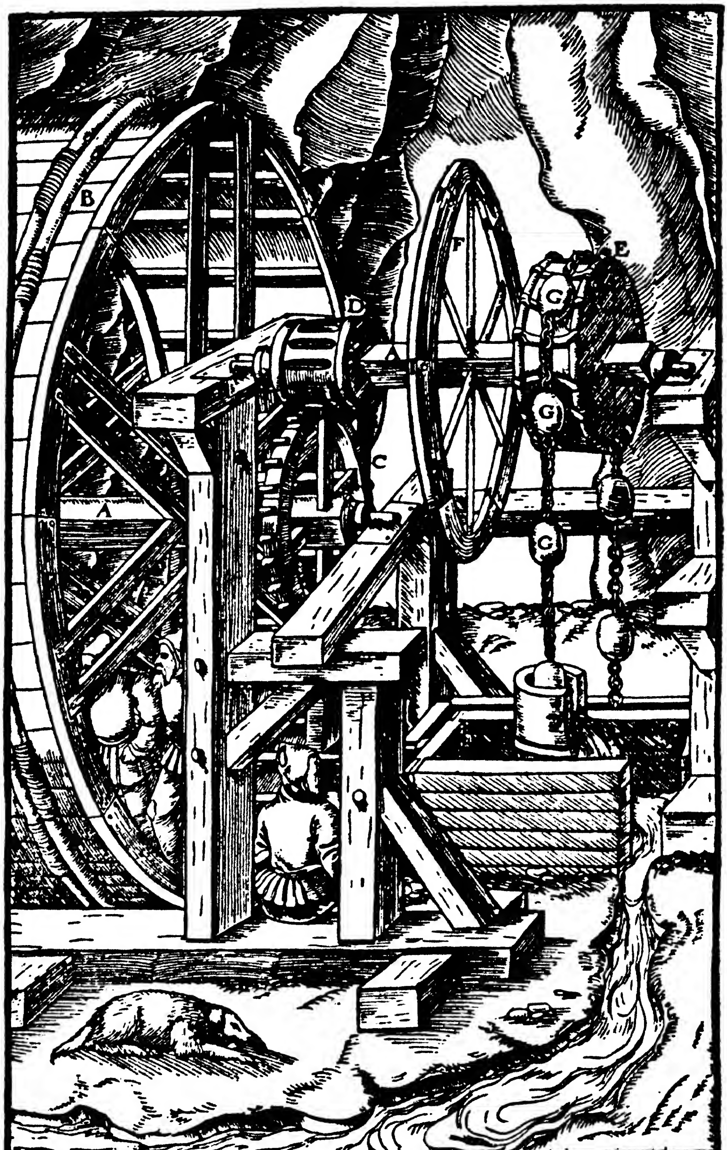


FIG. 34

Ball-and-chain pump operated by a tread-mill; from Agricola's *De Re Metallica.* (1553.)

those of 1898 by a greater measure than that by which the habits of 1800 differed from those of the year 1650. Only after the invention of sources of power other than those of man, beast, wind and water could an industrial civilisation be formed.

The steam-engine developed from the pump. In the fifteenth century the shortage of currency in Europe became acute. The purchase of goods from the East in exchange for silver made the demand for this metal very great and accordingly much attention was paid to mines. One of the difficulties of deep mining is the disposal of water and it was necessary to evolve mechanical pumps.

Georg Bauer (1494–1555), whose name was latinised, according to the custom of the learned, into Georgius Agricola, lived during most of his life in the Joachimsthal, in Bohemia. The district was the most important mining area in Europe, and Agricola, who was a physician by profession, spent his spare time learning all he could about mining both from the ancient authorities and from the practical miners and smelters. His best-known work *De Re Metallica* was published in 1553, and is a treasury of information about the technique of mining, the systems of ventilation, hoisting of ore, smelting of products and so forth. The problem of pumping is much discussed. Water was raised by systems of buckets or dippers attached to an endless chain or sometimes by the ball-and-chain pump, which is easily understood from Fig. 34. Various types of barrel pump, more or less approximating to the modern garden-pump, were also used. All these required much power to operate them and a mill wheel worked by a neighbouring stream was the common recourse. Sometimes the power of horses or even human labour was employed.

These simple methods could only cope with very limited quantities of water. As the ever-increasing demand for coal and metal in the seventeenth and eighteenth centuries led to the sinking of deeper mines, and the rapid growth of cities and the beginnings of habits of cleanliness called for larger water supplies, so the labour of horse and man became unable to fulfil the demand. Water-power could sometimes be employed to raise water (see Plate I), but an urgent need was felt for a plentiful source of power available at any time or place.

In the sixteenth and early seventeenth centuries the notion of doing work by the condensation of steam was suggested, but probably not applied. The Marquis of Worcester about 1650 probably made a machine of this kind. Steam was admitted to a boiler and was there condensed, leaving a partial vacuum into which water was admitted by a pipe leading to the source from which the water was to be pumped. Steam was then admitted once more to the boiler and forced the water out of a second pipe. Engines working on this principle were reintroduced from 1698 on by Savery (Plate XIII); the principle is still applied in the Pulsometer pumps. Attempts were made to use Savery pumps as sources of power by causing them to pump water on to a mill-wheel, but the efficiency of such machines would be very low. Between 1690 and 1700 Papin in Germany designed an engine in which water was boiled in a vertical cylinder, in which was fitted a piston. The steam raised the piston. The fire was removed, the steam then condensed, leaving a partial vacuum; the piston was forced down again by the pressure of the atmosphere. The fire was then replaced and the cycle was repeated. This machine was not a practical success.

The first true steam-engine (Plate XII) was the pumping-engine of Newcomen (1705). A boiler (B) generated steam at low pressure. The heavy pump-rods (*i*, *k*) suspended from a rocking-beam drew up the piston which was suspended from the other side of the same beam. The cylinder (C) was thus filled with steam from the boiler and then shut off from the boiler by a cock. A jet of cold water was then injected into the cylinder, so condensing the steam and leaving a vacuum. The pressure of the atmosphere then forced down the piston, so rocking the beam and raising the rods which operated the pump. The engine was later improved by operating the cock and jet automatically by the motion of the beam, by the introduction of a safety valve, and by better packing of the piston. It should be noted that the pressure of the steam was not utilised.

These engines were further improved by Smeaton about 1770 and remained in use for many years; but even at this date James Watt had gone far towards devising the engine that was to supersede them.

The fuel consumption of the Newcomen engine was very high, and Watt was the first to grasp the necessity of economising heat; he was also the first to make steam-engines which were adapted to turning a wheel instead, as heretofore, of pulling a pump-rod. Watt's principles, which turned the steam-engine from a mining appliance to a world-power, were embodied in patents of 1769, 1781 and 1782. The most essential were as follows:

1. *The cylinder must be kept as hot as the steam that enters it.*

The Newcomen engine condensed the steam in the cylinder, which therefore at each stroke had to be heated by the steam from say 20° C. to 100° C. This heating,

of course, condensed much steam without getting any useful work from it, and indeed this type of engine consumed at each stroke about four times as much steam as was needed to fill the cylinder. Watt avoided this necessity by surrounding the cylinder with non-conducting material and by applying his second principle, namely that,

2. *Condensation is to take place in a separate vessel, the condenser, connected to the cylinder through a cock or valve and kept free from accidentally-entering air by a pump.*

The cylinder was thus kept continually hot and the condenser continually cold; so heat was not wasted in repeatedly changing the temperature of parts of the engine. His third principle was of even greater importance. Instead of using steam merely to make a vacuum in the cylinder, he also used its pressure to impel the piston. He therefore suggests:

3. *Employment of the expansive force of steam and, if necessary, dispensing with condensation.*

The engine with these improvements was much more efficient, but still employed the clumsy rocking-beam. In 1781 Watt dispensed with the beam and used devices to convert the back-and-forth motion of the piston into the rotary motion of a wheel. He did not at first employ the familiar method of the crank, for a rival had patented this.

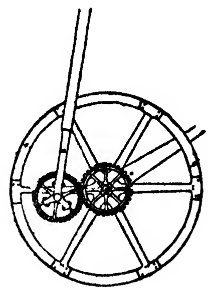


FIG. 35
Planet wheel device for converting reciprocating motion of beam into rotary motion

In 1782 and shortly after, he introduced two most important advances. First was the use of double action, i.e. the application of steam to one side of the piston while a vacuum was applied to the other; this doubled the duty done by each cylinder. Secondly he introduced

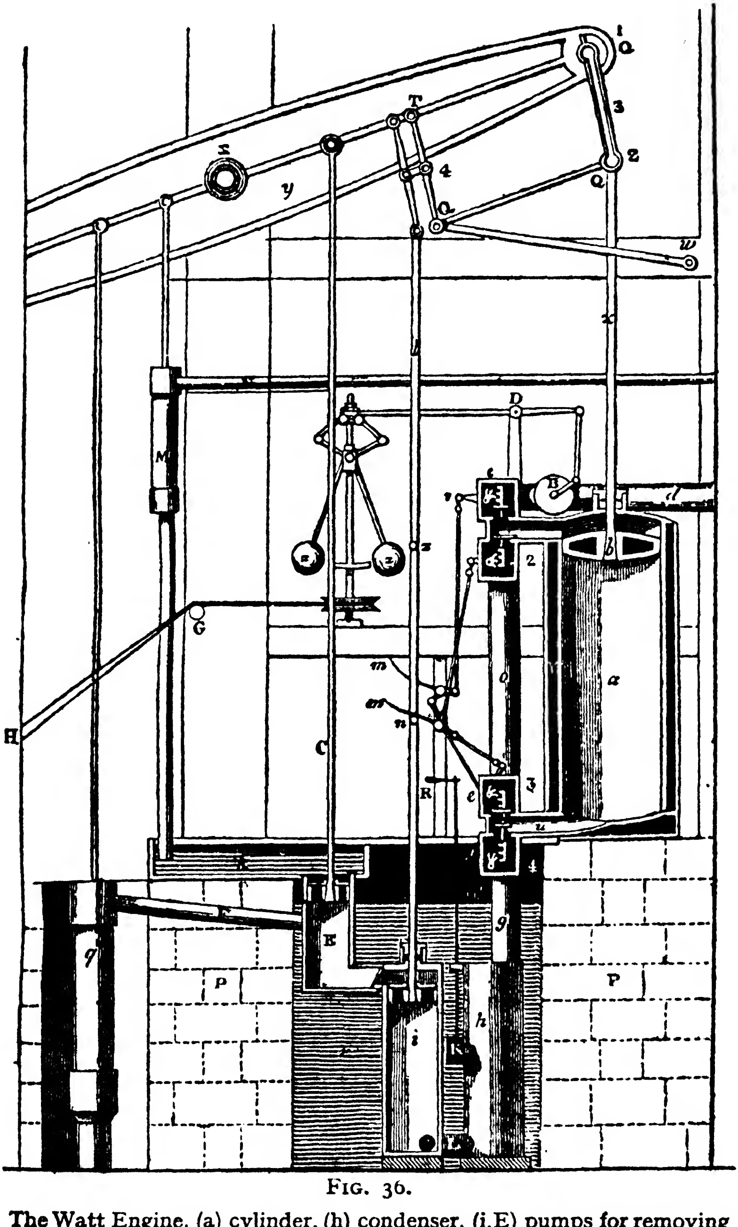


FIG. 36.

The Watt Engine. (a) cylinder, (h) condenser, (i,E) pumps for removing air and water from condenser, (z) governor.

the plan of stopping the admission of steam when the piston had travelled over but a part of its course and then allowing the expansion of the compressed steam to complete the stroke. This effected considerable economy. Finally he provided for steady running by the use of the throttle valve and governor which automatically cut down the steam supply to the cylinder if the rate of running of the engine increased—e.g. on account of the lightening of its load—and *vice versa*.

Watt may be said to have created the steam-engine as a practical proposition. Its uses now developed in two main directions; firstly in the driving of machinery, secondly in the field of transport.

In 1782, when the improved steam-engine was first available, there was not much machinery to be driven, for most of the world's crafts were still carried on by the old manual methods. Indeed it was only of recent years that it had been possible to make the castings required for the steam-engine. In 1720 some 20,000 tons of pig-iron were made yearly, mostly by smelting with charcoal: by 1788 this had increased only to 70,000 tons: the growth of the use of machinery raised this to 825,000 tons in 1800 and to 1,825,000 tons in 1830. The first important adaptation of the steam-engine was, as we have seen, to the pumping of water; the second was to the driving of textile machinery. Improvements in spinning and weaving had begun about 1720 and between 1770 and 1780 there had come into use textile machinery of a kind which required to be driven by power. At first water-power was used, but when practical rotary steam-engines appeared, the English textile trade developed enormously and brought with it gigantic prosperity. Looms and other machinery began to be made of iron

instead of wood. Other industries rapidly took to the use of power. Saw-mills were at an early date run by steam. Steam-printing came into use from about 1815. The gas industry, which became important from 1814 onward, required a good deal of machinery, as did also the chemical trades which supplied sulphuric acid, soda, chlorine, bleaching-powder, alum and other chemicals required in the textile industry. These, and above all, the locomotive and steamboat industries, required engines and machinery; the production of these caused the technique of manufacturing machine parts to improve. Thus arose the science of mechanical engineering, which became important from 1820 and reached huge proportions in the age of the building of railways and steamships (1830–1850).

The materials available for machinery were, as now, cast-iron, brittle but easy to cast into heavy machine parts; wrought iron, tough but laborious to make and requiring to be forged, not cast; and, lastly, steel. Steel in those days was expensive, for it was made by a lengthy process of heating wrought iron with charcoal and melting the product. The production of machinery was much more difficult and required much more skilled labour than in our age of cheap steel castings: it was only after 1860 that Bessemer and the Siemens brothers reduced the cost of steel to less than a fourth of its earlier price and so made it into a constructional material. The years from 1800–50 may be called the Age of Iron; 1850–1900 the Age of Steel.

The development of railways was the greatest feature of the world's history in the years 1825–50. The earliest locomotive was made by Cugnot in France as early as 1769, even before the improvements of Watt, but owing to the

troubles of the inventor's patrons it was not fully developed. Murdock and Watt made a small model locomotive in 1784. The first locomotive which was put to practical use was that built by the Cornishman, Richard Trevithick, in 1804. Railroads had been in use long before locomotives, and it was well known that a horse could haul a vastly heavier load on rails than on the road. Trevithick's locomotive, which had a flue-boiler and a vertical cylinder, appears to have been quite successful. Hedley in 1813 made a similar engine, which hauled coal wagons at the Wylam collieries.

George Stephenson was the first builder of a practical locomotive suitable for passenger work. Between 1813 and 1829 he built a number of locomotives. In the latter year a railway from Manchester to Liverpool had been nearly completed, Rennie and Stephenson being the engineers. It was earnestly and hotly debated whether the source of power should be locomotive-engines or fixed engines hauling the trucks by ropes. A prize was finally offered for the best locomotive-engine which should fulfil certain conditions. This was won by Stephenson's engine, the famous *Rocket*. The distinguishing features of this locomotive were, first, the fire-tube boiler, secondly, the use of a steam-blast to increase the draught of the fire. Its performance in hauling thirty passengers at a rate of twenty-five to thirty miles an hour astonished the world. The Manchester–Liverpool railroad was accordingly equipped with locomotives, and the idea of a cable-system operated by stationary engines was rejected.

Locomotives were rapidly improved, and by 1833 the link-gear had been invented; this allowed the engine to be easily reversed; by its aid the cut-off could be varied according to the load.

About this period road-locomotion was begun and between 1830 and 1840 Hancock had a regular service of steam-coaches running at ten miles an hour, but the badness of the roads made this means of transport unsatisfactory, and it was finally extinguished by the progress of railways and by hostile legislation.

The building of railways proceeded at a great rate, and the main outlines of the present British system were complete by 1850, when some 5,000 miles of railway were in use. Locomotive design was, of course, steadily improved, but the locomotive of the nineteenth century, in its broad features, followed the design of Stephenson's later engines.

A consequence of the success of steam-locomotion was that Great Britain found herself in the mid-nineteenth century selling steam-engines, locomotives and rails to the world. This trade built up a great school of skilled engineers and workmen and so made possible the use of many mechanical devices, the production of which would have been quite beyond the machine-shops of 1800–10. This engineering boom brought great prosperity to Great Britain and continued the enrichment which the application of power to the textile industry had begun.

The use of steam for water-transport dates from about the same period as the first construction of locomotives. The propulsion of boats by paddles is of early date and may go back to classical times. Throughout the eighteenth century many proposals were made for driving paddles by steam, but the first successful experiment seems to have been that of Jouffroy in 1783, using a Watt engine. The importance of the experiment was not realised by the French Government, and the attempt was dropped. Fitch and Rumsey independently experimented in America

in 1785–7: the former made a successful boat which ran two or three thousand miles. His means of propulsion was a beam-engine working three oars or paddles at the stern. He even experimented with the screw as a means of propulsion. In Great Britain Symmington, amongst others, experimented from 1787 onward. In 1802 he constructed a steam-tug which was used successfully for towing barges, while Bell in 1812 put into commission the first passenger-vessel built in Europe. From this period progress was rapid and by 1835 about thirteen hundred British steam-vessels were in use. Progress was also rapid in America; Fulton built a practical passenger river steamer in 1807 and thereafter the industry quickly developed. There were, of course, difficulties to be met, for it was not easy to discover what changes had to be made in the sailing ship in order to make it fit to bear the heavy stresses occasioned by the engine.

The date of the triumph of steam navigation may be taken as 1838, when two steamships, the *Sirius* and the *Great Western*, the latter of 1,340 tons and 450 h.p., crossed the Atlantic in fifteen days, half the time commonly taken by a sailing vessel. The Cunard Line was established in 1840, and has continued regular transatlantic sailings from that year to the present date.[1] The paddle-steamer remained as practically the sole type until about 1840, but in the years 1845–50 paddles were gradually replaced by the screw.

The first inroad of mechanisation into industry was far from complete. As late as 1850 many trades continued to carry on their labours by the ancient methods. Thus the cutlery trade of Sheffield was at this date almost all carried out by highly skilled hand-labour. The persistence

[1] Amalgamated with the White Star Line in 1935.

of hand-labour was here due to the craftsman's excellence: in other trades there was a darker cause. In the first half of the nineteenth century tragically low wages were given to woman and child factory workers: consequently it paid the manufacturer to employ unskilled labour to perform tasks which in a later age were performed by machinery.

CHAPTER VII

THE AGE OF SCIENCE

THE CONFLICT OF SCIENCE AND RELIGION IN THE NINETEENTH CENTURY

DESPITE the attacks which during the eighteenth century had been made upon revealed religion, the greater part of the educated public of the eighteen-thirties believed that the Bible was throughout inspired by God and literally true. The Bible is not a text-book of science, and cannot be said to give any definite pronouncements on the history and nature of the world. Theologians, however, regarded Holy Writ as capable of giving information on every matter of importance, and by their expert interpretation gradually built up a Biblical cosmology. The Fathers of the Church had come to the conclusion that the Bible was to be interpreted as giving its authority to certain propositions, among which were the following:—

That the date of Creation was recent, not earlier than 4000–5000 B.C.

That the process of Creation occupied six ordinary days.

That Adam was created perfect in morality and intelligence, that he fell, and that his descendants have shared in his sin and suffered for his fall.

That God, being utterly good, could not have created anything evil.

That there was an universal deluge, the only human and animal survivors of which were preserved in an ark.

To-day our minds are so imbued with the principles of development, evolution and progress, that it seems to us almost incredible that, only a hundred years ago, the world was generally thought of as substantially unchanging, only a few thousand years old, and as having come into existence by a half a dozen exercises of a Creative Fiat. None the less so it was believed.

The destruction of these archaic conceptions came about in three ways. First of all the rationalistic writers of the eighteenth century (p. 139) and their successors such as Comte had advocated the value of Reason and decried that of Faith in Authority. They had, moreover, shown that the sacred books were self-inconsistent and not always in accord with a rational morality.

Secondly the inspired character of the books became open to doubt. It became increasingly apparent that the "Mosaic" account of Creation and the early history of the world was not written by Moses under the direct inspiration of God, but that it has the production of two or more authors, dating only from 800–500 B.C. and showing—most disconcertingly—strong evidence of the influence of Assyrian mythology. The reasons for adoption of some books as canonical, i.e. sacred and inspired, and of others as apocryphal and not inspired, were shown to be arbitrary and of entirely human origin. Finally the same standards of evidence were applied to Biblical writings as to profane works, a process which led many to the conclusion that the Bible, while containing lofty moral teaching, was by no means reliable as a historical source.

The rationalist philosophers and the Biblical critics

made very little impression on the public. The battle royal was, in fact, fought over the factual truth of the Creation story. It is perhaps notable that the only parts of science which were seriously engaged in the conflict with religion were Geology and evolutionary Biology. The creation of the world and the place of man in it was a fundamental of religion as then conceived. The conflict of the Biblical accounts of miracles with what was known of Physics, Chemistry and Biology, though hotly argued, was but a minor skirmish.

The first difficulties which arose were in connection with the date and manner of the Creation. The studies of the upper strata of the earth were in their broad outlines completed before 1850: they showed very clearly that most of the rocks had been deposited from water: water was also known to be still depositing similar strata at an exceedingly low rate. It became apparent that many millions of years were required for the deposition of the vast thicknesses of strata which the geologists found. The slow weathering of rocks, the production of vast areas of land by the deposition of mud in the deltas of such rivers as the Nile and Mississippi, confirmed the necessity of a great age for the earth. On the other hand, the Bible story, while giving no exact chronology, indicated an age of about six thousand years. This discrepancy was serious. The existence of fossil remains of creatures, such as the giant lizards, which found no place in the Bible story, were disturbing; even more so were the remains of primitive man.

The response of the geologists who could not disbelieve either the scientific evidence or the Bible story was to admit the remote date of Creation and to substitute for each "day" of Creation a period of undefined vastness.

Their position, then, was that God had created the various species at certain epochs of the world's history, but that these epochs were separated by great periods of time. But many difficulties remained. God was utterly perfect and could not possibly create anything evil; the evil of the present world was accounted for by the sin of Adam: how could it then be that the pre-Adamite world of the dinosaurs showed every evidence of the same carnage and brutality as exists to-day?

The problem seemed almost insoluble, unless, as in some speculations, the Devil was believed to have led these innocent creatures astray. But the picture of Satan seducing an ichthyosaurus from its native innocence was too archaic even for the eighteen-fifties. By those who supported the substantial truth of the Biblical account much was made of the supposed fact that the order in which the creation of plants, reptiles, birds, fish, etc., was declared to have taken place, corresponded to the order of their appearance as deduced from the occurrence of fossils in the successive strata. In fact the coincidence or order proved to be by no means exact, and this argument for the Divine origin of the Creation story was later demolished.

The obviously impossible story of the Universal Deluge was toned down to a local deluge (due to a sinking of land) from which Noah escaped in an Ark, taking with him only such animals as might be useful to him.

These heart-searchings did not greatly affect the general public, whose attitude was that, if Geology disagreed with Holy Writ, so much the worse for Geology. Few, even among geologists, did more than search for a reconcilement of the divergence between science and revelation.

But in 1859 the publication of Darwin's account

of his theory of Evolution in his *Origin of Species* put an altogether new complexion on the controversy.

The theory of Evolution is discussed elsewhere (pp. 279–281); suffice it here to say that Darwin put forward, on grounds supported by evidence strong enough to convince most of the younger men of science, the theory "that the innumerable species, genera, and families of organic beings with which the world is peopled have all descended, each within its own class or group, from common parents and have all been modified in the course of descent." This modification he supposed to take place by the process of *Natural Selection*. By this he meant that all organic beings are variable, the offspring differing to a small and inconstant extent from their parents: in the struggle for life (which exterminates the majority of all organisms before they have offspring) those individuals who have varied from their parents in a manner advantageous to their preservation would be *selected* or *preserved* by nature. Thus if a wild horse escapes death at the hands of carnivora by its swiftness, the slowest horses will succumb and the swiftest will have the greatest opportunities of breeding; horses will, therefore, become steadily swifter. In fact the remains of horse-like creatures found in the rocks show a steady modification in the direction of speed as we approach modern times.

These, the essential doctrines of Darwinism, gave great offence to the theologians. In the first place they ran contrary to the Mosaic account, wherein the animals are said to be created as they are to-day, a doctrine which implies fixity of species. In the second place the time needed for evolution was clearly enormous, for there was evidence that no appreciable modification had taken place in historic times; this confirmed the doubts, already

raised by geologists, as to a recent Creation. But the really serious matter was Darwin's extension of the theory to Man, who, on this theory, was clearly descended from some non-human ape-like creature. This was degrading enough, but when it was considered that orthodox theology led to the belief that apes have no immortal souls such as men have, there arose the insoluble problem of the manner in which the one could pass imperceptibly into the other. A tremendous battle ensued. Darwin himself was completely reticent on the religious question—his private views being those of an agnostic inclined to theism. But T. H. Huxley, who was as great a controversialist as biologist, fearlessly took up the cudgels for Evolution. The scientific world was divided. Owen and Sedgwick did not believe in evolution, and many of the older geologists and biologists sided with them: the younger men in general welcomed the theory.

The result of the controversy, as we all know, was the almost complete abandonment of the belief in special creation. Huxley's brilliant essays and works published between 1860 and 1890 may be said to have established and to have made into a general habit of thought the view that religious writings must be treated as any others with respect to the information they give concerning material facts, and that their evidential value is not greater than that of uncanonical writings from similar sources. He coined the word "Agnostic" to signify one who believed that it was not possible to have certain knowledge as to the supernatural. To-day agnosticism and indifferentism are the views which characterise the modern world. The service which this controversy rendered to science was great, to religion perhaps greater; the religious man to-day is not troubled by a farrago of fables nor

by the necessity of literal adherence to a book. If he finds the Kingdom of Heaven, it is within him.

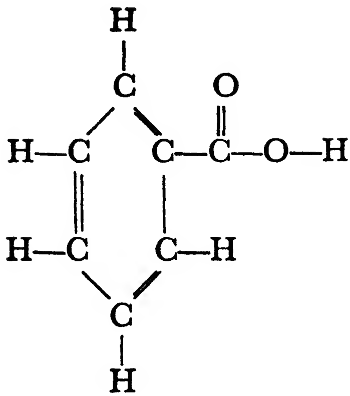
The attempts to set up scientific creeds have not met with much success, because science can tell us almost nothing of ethics or of metaphysics. The scientific creed can have nothing but energy and matter in its make-up, for on no other subjects can science give us information. If ever thought becomes explicable in terms of energy and matter, there will be room for a scientific religion: until that unlikely event, human conduct will be guided by a mixture of more or less irrational considerations, prudential and emotional, from which a religion may be formed. Science is the only useful way of dealing with *things* so as to modify them to our will: judging from the effect of single men upon the world, the symbolic and mystical method of thought is the useful means for evolving ideas which may modify *minds*.

THE NATURE OF MATTER: PROGRESS SINCE 1850

The chemist in 1850 had progressed a long way beyond Dalton in practice, but not so far in theory. He had found the relative weights of most of the atoms and from these he could obtain the formulæ of very many compounds. But he was troubled by the difficulty of deciding whether the number of a particular kind of atom in a compound was one or more. Thus water he knew to contain one gramme of hydrogen for every eight grammes of oxygen. Did the molecule of water contain one atom of hydrogen of weight eight units? Or were there two atoms of hydrogen weighing one unit each to one atom of oxygen weighing 16 units? This question was cleared up by the application

of Avogadro's law, first put forward in 1811, but brought to light again by Cannizzaro in 1858. By arguments too long to be given here, but available in any chemical text-book, it was found possible to settle definitely the relative weights of the atoms and of most molecules. The real weights were not known till 50 years later: but it was known that an oxygen atom was 15.97 times as heavy as a hydrogen atom and a gold atom 197.2 times as heavy, and so forth.

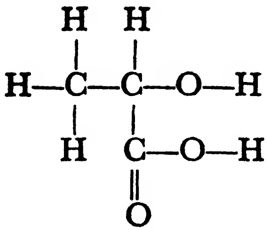
It was then possible to know exactly how many and what kinds of atoms were in each molecule. Thus it was now known that benzoic acid had the formula $C_7H_6O_2$ (p. 238): but the problem of the chemist was to discover how these fifteen atoms were arranged to form a single molecule. The organic chemists were the chief agents in solving this type of problem. Certain small groups of atoms, they found, conferred particular properties on the substances which contained them. Thus, for example, the group —CO_2H conferred acidic properties on an organic compound. Each atom, too, had a fixed combining power or valency: thus a carbon atom could combine with a maximum of four other atoms, an oxygen atom with two, a hydrogen atom with one. Chemists then pictured the molecules of compounds as being made up of atoms linked by "valency-bonds" which they could not explain but pictured by a line. Thus the compound benzoic acid formerly known only as $C_7H_6O_2$ was soon shown to have its atoms linked in this pattern:



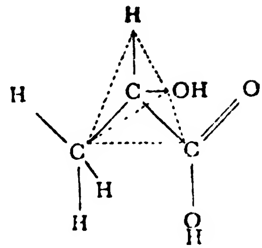
Each letter denotes the appropriate atom (C = a carbon atom, H = a hydrogen atom, O = an oxygen atom); each line denotes a valency bond.

The conception worked extraordinarily well in the realm of organic Chemistry and was of definite though lesser aid in inorganic Chemistry. The chemists would have been slow to assert that molecules were really composed of material atoms arranged in this manner: they only asserted that the hypothesis of such an arrangement served to explain the chemical behaviour of benzoic acid. In fact the formulæ were remarkably accurate pictures of the molecules. The chemists had always drawn their atom-patterns on paper and naturally, though with no justification, thought of all the atoms in the molecules as lying in a plane. The work of Pasteur, amplified and interpreted by that of van't Hoff and le Bel showed that for carbon atoms, at least, this was not true, but that the four atoms combined with a carbon atom were distributed evenly in space around it. This is now known to be true of most atoms which combine with three or more other

atoms. Thus the lactic acid molecule had not the plane structure.



but the tetrahedral structure.



The organic chemists proceeded to work out a gigantic edifice of science entirely based upon the atom-patterns they had worked out: the system worked beautifully and enabled them to make thousands of new compounds, drugs, dyes, solvents and so forth, despite the fact that no one had the faintest idea as to what an atom was like.

Meanwhile the inorganic chemist discovered more and more elements, and by 1875 some sixty-three were known. Elements were still looked on as having been immutable since Creation, much as were the species of animals before 1859. One or two attempts to trace likenesses between them had been made, but had attracted little attention. Then in 1869 the Russian chemist Mendelejeff revolutionised Inorganic Chemistry by showing that the elements could be classified in eight definite groups or families with the members of each of which had similar properties, and showed that the behaviour of an element was to some extent a function of the weight of its atoms.

This classification of the elements was of great value, though there were many curious slight irregularities. It was clear that the different elements were in some way related, but until the twentieth century the nature of the

connection between them remained quite obscure. New elements were discovered from time to time, and all fitted into Mendelejeff's scheme; and in the years following 1894 its correctness was clinched by the discovery of five new elements, the gases helium, argon, neon, krypton, and xenon: these formed a complete new group of elements which fitted perfectly into Mendelejeff's system.

By the 1880's chemists were beginning to feel a little restive about atoms. Their whole science was built up on the assumption of atoms, but of direct physical evidence for the size, shape and weight or even for the existence of atoms, there was none.

In 1897 a new era dawned. Radioactivity was discovered. Mme. Curie and others discovered several new elements which were found to be giving off rays of a new type. Rutherford and Soddy in 1902 showed that the atoms of these new elements were breaking up and that they were being transmuted into other elements. This staggering discovery showed that the elements had some common factor: the further work of Rutherford unravelled this.

Meanwhile the physicists had by several refined methods discovered the approximate size and weight of the atoms; it appeared that an average atom might be about a ten-millionth of a millimetre in diameter and a ten-thousand-million-million-millionth of a gramme in weight. They had also discovered a particle called the electron which was the ultimate particle of ordinary negative electricity. This seemed to be contained in all matter and was about two thousand times lighter than the lightest atom.

Rutherford soon proved that an atom consisted of a cloud of these negative electrons surrounding a minute positively charged nucleus containing almost the whole of the mass of the atom. The work of van den Broek and

Moseley led to the idea that this nucleus was the characteristic part of the atom, and the distinction between, say, a lead atom and a gold atom lay in the fact that the nucleus of the former had an electrical charge of 82 units and that of the latter 79 units. Soddy showed that Mendelejeff's scheme had had its difficulties because the elements were classified on a basis of atomic weights instead of nuclear charges, which run nearly but not quite in the same order as the atomic weights. Niels Bohr in 1916 suggested a theory of the atom which, at least by chemists, is still generally held. Other theories explain the behaviour of the atom even more exactly but require to be expressed in complex mathematical terms. Our present belief about the chemical elements and their compounds is somewhat as follows:—Each one of the ninety elements is characterised by having atoms with one particular nuclear charge which varies from 1 unit for hydrogen to 92 units for uranium. The nucleus of the atom consists of protons (particles which have a positive charge of 1 unit and a weight of 1 unit) and neutrons[1] (which have no charge but a weight of 1 unit): the number of protons is always the same in all atoms of the same element, but the number of neutrons may vary somewhat. Surrounding this minute nucleus as centre there are comparatively large groups or shells of electrons (negatively charged) equal in number to the protons in the nucleus. Thus the element chlorine is made up of two kinds of atom:

1. with (*a*) nucleus containing 17 protons, 18 neutrons and (*b*) outer cloud of 17 electrons.
2. with (*a*) nucleus containing 17 protons, 20 neutrons and (*b*) outer cloud of 17 electrons.

[1] Discovered by Chadwick in 1932.

These two kinds of atom are practically indistinguishable.

This view is a vast simplification. Instead of ninety unrelated kinds of atoms constituting the substance of the world, we have but three kinds of particles: protons, neutrons, and electrons. The behaviour of these minute particles is quite unlike anything we experience with larger masses: they cannot be conceived as having any appearance or any of the secondary properties we associate with matter in bulk. They have not even an accurately definable position: they are to be thought of only in terms of mass and energy.

This new view of the atom explained Mendelejeff's scheme. The elements of any one of his "groups" had a similar pattern of electrons in their outer cloud, and were similar in their properties because it is only this outer cloud that comes into contact with other atoms.

The reason why the atoms of elements combine to form the molecules of compounds was also for the first time explained by supposing that an atom could donate some of its electrons to another atom or share them with it, so setting up an electrical attraction between them. The subject is still in its infancy, for the mathematical technique necessary for calculating what the electrons in an atom will do is still to seek: when, if ever, it is found, Chemistry will become a mathematical science.

Not only has the atom of late given up some parts of its secrets but the work of Laue and the Braggs has enabled us to find out precisely where the atoms in the molecules lie. It has long been known that the beautiful regularities of crystals could be explained if they were supposed to consist of molecules arranged in a regular repeating pattern like that of bricks in a wall or flowers on wall-paper. Bragg studied the way in which X-rays are

reflected from crystals and worked out where the layers of atoms, capable of reflecting X-rays, lay. Mathematical treatment enables the molecule itself to be mapped out as accurately as if we could see it. These results have confirmed most of the chemist's work on formulæ and have thrown a flood of light on a number of difficult cases.

We picture the solid world, then, as made up of minute molecules of chemical compounds in constant vibration about positions which lie for the most part in regular geometrical patterns—a Pythagorean conception. In liquids and gases the motion of the molecules is unfettered and chaotic. These molecules consist of atoms arranged in a fixed pattern but also in vibration. These atoms consist of electrons, protons and neutrons, probably executing most complex motions. What lies behind these ultimate particles is wholly unknown. No doubt all these theories will be modified as the years go on: they are, however, a closer approximation to the truth than were those of former years.

INORGANIC AND PHYSICAL CHEMISTRY SINCE 1850

The science of Inorganic Chemistry, the study of the elements other than carbon and of their compounds, has made steady progress since 1850, but has shown no such great development as the other branches of that science. Twenty-eight new elements have been discovered since then, but the man in the street knows the names of only three of them, helium, neon, and radium. The two really important theoretical discoveries of the period are, first the discovery, between 1892 and 1898, by Rayleigh, Ramsay and Travers of the five inert gases, helium, neon, argon, krypton, and xenon, the first elements yet

discovered which would not combine with anything to form compounds; and secondly, the discovery of the radio-elements—radium, polonium, actinium, etc., by Mme. Curie, Rutherford, Soddy and others. These are outstanding discoveries. Thousands of compounds, of course, were prepared and investigated during these eighty years, but not many of them are to be regarded as more than bricks in the growing city of science.

The so-called Physical Chemistry—which may roughly be regarded as the application of the methods of Physics to the science of Chemistry—had made enormous progress, and to it is due the existence of many of our chemical industries.

The investigation of the nature of solutions has proved very fruitful, for almost all chemical operations are conducted in solution. The study of the action of the electric current on chemical substances has been investigated, and a great number of chemical processes are now conducted by electrical methods. The manner in which the rate at which chemical reactions take place is influenced by external conditions and is another chapter of theoretical Chemistry, which has rendered it possible to obtain good yields of products from apparently unsatisfactory reactions. The study of *catalysis,* the process, as yet too little understood, by which the presence of a trace of a third substance can cause two substances to combine far more rapidly than without it, has also proved to be of the first theoretical importance.

The chemical industries have changed out of all recognition since 1850. Before that date, the concern of industrial Chemistry was almost wholly the production of acids and alkalis for the textile industry, soap-making, etc. This industry has, of course, continued and grown.

The old chamber process for making sulphuric acid still survives after a hundred years, but the new contact process has proved more suitable for making pure concentrated acid for the dye and drug industries. Caustic soda for soap-making and chlorine for bleaching are made simultaneously by passing electric currents through a solution of common salt. Common soda is made to a large extent by the Solvay process, the action of carbon dioxide and ammonia on common salt. The intense competition has caused the industry to change throughout in the direction of producing purer materials and of avoiding waste products.

A wide field has been opened by the synthetic nitrogen industry. Vastly increased populations have been taking food from the world's fields and excreting the nitrogen they contained *via* the sewers into the sea. To maintain and to increase the fertility of the soil farmers have needed to replace this nitrogen in a form that plants can assimilate —ammonium salts or nitrates; the making of these is a huge industry. Crude coal-gas contains ammonia—the nitrogen of long-dead plants: this is extracted and sold as ammonium sulphate. The nitrate deposits of Chile also provide a limited supply, but to-day the greatest part is made from the air. The nitrogen derived from the air and hydrogen derived from water are forced to combine to ammonia: alternatively the nitrogen and oxygen of air, together with water, are converted into nitric acid. This latter compound is needed in great quantities to make not only fertilisers but also dyes and explosives (p. 248).

The application of Chemistry to the immemorial art of smelting metals has created new industries and profoundly influenced engineering practice. The discovery of commercially valuable methods of making aluminium dates from about 1890, but the industry began to reach its

present stature only from about 1910. The steel industry has been revolutionised since its chemical principles have become known. Its mechanical development belongs rather to engineering (p. 308); but the discovery of the numerous special steels containing a small proportion of some less common metal—manganese, tungsten, vanadium, etc.—and used where particular qualities of hardness, toughness, or elasticity are required is a chemical development. Stainless steel, an alloy of iron 84 per cent., chromium 13 per cent., nickel 1 per cent. is a chemical discovery, the full results of which we have not yet seen. It is impossible to do more than mention a variety of other important industries allied to Inorganic Chemistry. High-temperature reactions in the electric furnace have yielded graphite for pencils, lubrication, and electrical work; calcium carbide from which are made acetylene, acetic acid and the fertiliser cyanamide; numerous abrasives such as carborundum. The photographic industry became important from about 1850 and required a variety of highly purified materials. The manufacture of pigments, paper, disinfectants, gas-mantles, weed-killers, oxygen, poison gases, serves to indicate the innumerable industries dependent on Inorganic Chemistry.

ORGANIC CHEMISTRY

Organic Chemistry was the term originally applied to the substances derived from organisms—animals and plants. These substances—as examples we may mention alcohol, tartaric acid, uric acid, sugar—were supposed to be formed only within living creatures by the operation of a mysterious vital force. They were known to consist

essentially of carbon, with hydrogen and other elements such as oxygen, nitrogen, sulphur, etc., and to be quite complicated, having commonly twenty or so atoms in their molecule. In this respect they were unlike the well-known inorganic compounds, and until the eighteen-thirties very little was known of their nature; but from 1832 onwards Liebig and Berzelius both developed the notion that their molecules were composed of groups of atoms, or *radicals*. Between 1830 and 1850 the idea of these groups of atoms being arranged on certain patterns or types was developed, but these conceptions were not very fruitful. After 1858 the idea of valency developed, and it was realised that carbon atoms were able to combine together to form long chains and that the exact form of the molecules of organic substances could be discovered. Organic Chemistry was then found to be the most regular and predictable department of Chemistry, and a vast number of organic compounds were built up: the total known to-day being more than half a million. The first fruit of the systematic study of Organic Chemistry was the discovery that many of the compounds contained in animals and plants could be made from lifeless materials in the laboratory—a discovery which may be thought of, first, as the beginning of the modern science of Bio-chemistry and, secondly, as contributing to the nineteenth-century materialistic view of life. The second result was the discovery of an enormous number of useful and interesting compounds and the foundation of several great industries. The third, and for humanity in general perhaps the most important result was that the new organic compounds, being closely related to the material of the human body, in many cases proved to be valuable drugs; we owe to Organic Chemistry almost all the materials

which distinguish our modern physician's equipment from that of his eighteenth-century predecessor.

Thus the most important function of Organic Chemistry is, perhaps, the discovery of effective drugs. Those used in modern Medicine are, in part, naturally occurring drugs such as strychnine and morphine: these were at one time used as plant-extracts, but they are now always purified by the chemist, being thereby freed from undesirable substances and also caused to be of exactly known potency. The majority of our drugs, however, had no existence until the organic chemist synthesised them. All the general and local anaesthetics without which modern surgery would be impossible are the work of the organic chemist. Analgesics such as aspirin; hypnotics such as paraldehyde and veronal; the new drugs, derived from organic compounds of arsenic, antimony, and bismuth, which are so effective against syphilis, sleeping sickness and yaws; the disinfectants of every type—these comprise only a few of the classes of drugs continually produced in the laboratory.

The dye-industry has been completely transfigured by the organic chemist. Before 1860 the dyes used were prepared from plant or animal products, and the range of colours obtained was very limited. The chief dyes were madder (reds and pinks), cochineal, and indigo. To-day the list of fast and brilliant dyes runs into tens of thousands. The first aniline dye to be made on the large scale was mauve, obtained by Perkin in 1856; new classes of dyes were discovered in rapid succession and a comparison of the bewildering varieties of shades to be seen in an exhibition of modern textiles with the limited range of colours found in a museum of old fabrics affords some measure of this development.

The advent of a new material is a rarity. Till late in last century all our objects of use and ornament were constructed of the ancient materials, linen, cotton, wool, silk, bone, ivory, horn, wood, glass, ceramics or metal. The introduction of rubber and vulcanite and later of celluloid was the harbinger of the age of plastics. The discovery by Baekeland in 1906 that phenol and formaldehyde combined to form a substance which could be moulded into all manner of objects and hardened by heat and pressure heralded researches which have led to the discovery of light, transparent, and bright-coloured plastic materials from which a vast variety of objects ranging from ash-trays to furniture can be made.

The artificial silk industry belongs also to this century. The power of transforming wood-pulp into strong and brilliant fabrics introduced a new textile material for the first time in thousands of years, and has transformed woman's dress.

Other industries dependent on Organic Chemistry can receive only a mention. Synthetic perfumes, poison-gas, modern explosives, oil-fuels, margarine, soap, sugar, starch, solvents, are a few of the materials in the making of which Organic Chemistry plays a large part.

The raw materials of Organic Chemistry are not many. Chief of these is coal. When coal is distilled it produces coke, coal-gas, a watery liquor containing ammonium compounds, and an exceedingly complicated mixture known as coal-tar. When this is distilled it gives benzene, toluene, carbolic acid, naphthalene and anthracene, road-pitch being the residue. These materials are worked up into an extraordinary variety of drugs, dyes, solvents, etc. The other chief sources are sugars and starches, cellulose, oils and fats from plants. Since such a huge variety of

products is made from so few materials, the manufacture must necessarily often proceed by many and complicated stages. The work therefore needs much skilled supervision, and through dependence on the workman rather than the trained chemist, England went far to lose its fine-chemical industry to Germany, and it is only since 1916 that a substantial drug and dye manufacture has here been built up again.

PHYSICS SINCE 1850

The science of Physics, apart from the study of electricity, was on the whole well advanced in 1850. Since that time the discovery of the electrical nature of radiation and matter has been the most conspicuous achievement of pure Physics. The other great development, even more fundamental though of less immediate significance, has been the scientific study of energy.

In the years immediately preceding 1850 the notion of the Conservation of Energy became defined. Several physicists contributed towards the notion that energy existed in the various forms of heat, work, radiation, chemical energy, and that in none of the changes of the world was energy lost, but that it underwent only a transformation. Rumford (~~p. 161~~) and others studied the production of heat from work: Carnot (1824) was the first to study mathematically the way in which work could be obtained from heat. Helmholtz in 1847 enunciated the general notion of the Conservation of Energy.

The next stage was the formation of the science of thermodynamics which gives a mathematical treatment

of the transformations of energy, and underlies a great part of theoretical Physics and of Engineering. We owe this largely to William Thomson, Lord Kelvin (1824–1907) and to Clausius (1850). From thermodynamics arose one of the present greatest problems of Cosmology. All processes involving the production of work are shown to arise by the change of energy from a greater intensity to a less intensity. Thus in a steam-engine no energy is lost; the heat energy of the steam put in is precisely equal to the work produced by the engine together with the heat given out in the exhaust steam and by leakage: but the intensity (e.g. temperature) of the energy taken in is greater than that of the energy given out. The important conception is that the contrary process, i.e. an increase of intensity of energy in a system taken as a whole, does not occur. Throughout the universe there is a steady degradation of energy from high intensity to low intensity and its ultimate fate appears to be an eternal dead-level of uniform temperature and stagnation. Boltzmann (*c.* 1860) interpreted this as a general tendency of the universe to increased disorder, due to the fact that the degeneration of ordered arrangement into chaotic disarrangement is always mathematically more probable than the restoration of order from chaos.

The study of energy is fundamental to theoretical Physics, but its practical results are less obvious than those of many branches of that science. They are to be seen in the development of the efficiency of steam-engines and internal-combustion engines and the consequent cheapening of power. A quite important application, developed in the twentieth century by Dewar and others, is the liquefaction of gases, which depends on the work done in separating the molecules of a gas when it expands

from a high pressure to a low pressure. This work is derived from the heat energy (the speed of molecular motion) of the gas and so causes its temperature to fall. The oxygen industry, and the manufacture of neon and other rare gases for discharge lamps depend on the liquefaction of air in this way.

The greatest development of Physics since 1850 has been in the understanding and use of electricity. Before 1850 it was realised that there was a close relation between electricity and magnetism. The galvanometer and the electromagnet had already been discovered: the years between 1850 and 1875 saw the theory of the relation of electricity and magnetism worked out by Kelvin, Clerk Maxwell and others. The scientific interest of this is considerable, but the practical applications were gigantic.

The first important use of electricity was the development of the telegraph, a substantial advance towards the increasingly close inter-connection of the whole world, which, for good or ill, began with railways and steamships and has not yet ceased to develop. Morse in 1845 erected the first practical telegraph system—in principle simply an electrical circuit with an interrupter key and an electromagnet, which when energised by a current deflected a needle or operated some form of recorder. The idea was taken up very quickly. In England, Wheatstone and Lord Kelvin worked out the theory and practice of submarine telegraphy. The first cable was laid between England and France in 1850, but it soon broke. Such experiences showed that these cables required great mechanical strength and in 1858 the first transatlantic cable was laid. The need for sensitive instruments to detect the feeble signals led to Kelvin's invention of the mirror galvanometer and of the syphon

recorder. From 1871 a system for sending more than one message at the same time was invented, and this was steadily developed until 2500 letters a minute could be sent by a single cable. The telephone and wireless telegraphy have in recent years largely supplanted the telegraph.

A great electrical industry began in 1876, when the first telephone was constructed by Graham Bell. The first commercial telephone exchange was opened in 1878. The number of subscribers in the U.S.A. was about 50,000 in 1880, 225,000 in 1890, 4,000,000 in 1905, 10,000,000 in 1915 and 20,000,000 in 1930. The development in European countries was parallel but slower.

The development of the telephone led to a more practical study of sound, and indirectly to Thomas Alva Edison's invention of the talking-machine in 1876. The development of the original instrument into one which gave a tolerable reproduction of music was very slow and was chiefly due to Emile Berliner in the 'eighties and 'nineties. Progress was rapid from 1900 onward, and was greatly accelerated by research on broadcasting.

One of the greatest events of the nineteenth century was the discovery of the dynamo. Electricity derived from batteries whose "fuel" was the expensive metal, zinc, could only be of practical use where small quantities of current were required. The growth of electroplating made it urgent that a cheap source of electricity should be developed. Even as early as 1831 Faraday had generated an electric current by rotating a copper disc in the field of a magnet. Wheatstone, Siemens and others gradually improved the dynamo, which became of practical value from about 1870. Edison in 1878 produced the first

dynamo of high efficiency; this converted 90 per cent. of the power supplied to it into electricity in place of only 50 per cent. as formerly. In this early phase only direct current was produced: alternating current supplies were developed from 1885 and have for the most part superseded direct current: since that period generators have been built in larger and larger sizes. At first a multitude of small stations were built. The recent tendency has, however, been for several large stations to co-operate in transmitting current at very high voltage to transforming stations where it is reduced to a comparatively safe figure. The story of the development of electrical supplies has been that of increasing demand bringing about bigger units of supply, so leading to lower prices: these lower prices make new uses possible and the demand further increases. In this country the critical period was that of the war 1914–18. In 1906, the average price of a unit of electricity was 2s. 3d. and the total generating power was 1,000,000 kw. The war produced new and urgent demands for power. To-day the average price is less than 2d. a unit and the total power in use is more than 4,000,000 kw. The main uses for electricity have been for lighting, traction, the driving of machinery, electric furnaces and domestic heating.

Electric lighting by the arc-lamp started as soon as dynamos were efficient enough to give a reasonable supply of current. Edison invented his carbon-filament lamp in 1878. The efficiency of modern lamps is now three-and-a-half times that of the early carbon filaments.

Electric motors of a kind had been devised as early as 1831, and a battery-driven locomotive was tried out as early as 1838. But until the dynamo provided low-priced current, electric traction had to remain experimental.

The first electric railway was installed in 1883 at Portrush in Ireland. In the late 'eighties and 'nineties electric trams became popular; these are now giving place to petrol-driven vehicles. Meanwhile the electrification of railways makes continued progress.

The use of the electric motor in industry very soon began, but only in the last twenty years has it become the chief method of using power. Thus in 1900 only 3 or 4 per cent. of the total power used in America was electrical, in 1927 70 per cent. of the total power was employed in this form. The use of electricity for domestic heating has only become general since 1920, but it has long found a use in the chemical industry for heating furnaces, because the passage of a current through a conducting medium can give a much higher temperature than can the burning of coal or other fuel.

The knowledge of the nature of the electric current lagged much behind its theoretical investigation and practical exploitation. There was not much attempt to investigate the nature of electricity until the 'eighties: the tendency was to think of electric phenomena only in terms of the forces they exerted—the stresses and strains they set up in the hypothetical ether of space. Faraday's experiments on electrolysis (1833) showed there was a unit quantity of electricity associated with the atom of matter, but this unit was not thought of as representing an indivisible portion of electricity or primary electrical particle. The suggestion that electricity might be atomic was mooted from time to time, but a definite theory of this kind was first clearly set out by Stoney in 1891. He applied the name *electron* to these hypothetical units of electricity. His theories were not generally adopted and it was only in 1897 that the real existence of the electron

was proved. In 1879 Sir William Crookes had shown that when an electrical discharge was passed through a fairly high vacuum, the "cathode-rays" so produced were a swarm of fine particles "which with good warrant are supposed to constitute the physical basis of the universe." This revolutionary conclusion was not generally accepted. In 1897 J. J. Thomson proved conclusively that these cathode rays were particles whose mass was of the order of a thousandth of the mass of a hydrogen atom. The belief that the electric current consisted of a stream of these minute particles was gradually adopted about the turn of the century and accepted beyond all doubt by 1910. The discovery that the electron was not only a constituent of electricity but also of all matter effected the greatest unification of our world-view which has yet come about.

A group of great discoveries has followed from the investigation of radiation. It was generally believed from 1830 onward that light was a wave in the hypothetical "luminiferous æther," but great difficulty was experienced in devising for the æther a set of properties which would enable it to carry the sort of vibration which light appeared to be. The earliest theory was that the æther vibrated like an elastic solid—wobbled, in fact, like a jelly. It was shown, however, that the æther vibrated in a different way from any matter. The greatest advance was made by Clerk Maxwell, who put forward in completed form, in 1873, the theory that light was an electromagnetic oscillation. He worked out the equations governing such vibrations: the results agreed fully with the behaviour of light, and by the end of the nineteenth century the theory of light had reached almost complete perfection. The opening of the nineteenth century brought, however, a

totally new set of problems (p. 259), and while at present our knowledge of radiation is far more than in 1900, our certainty about its nature is far less. Maxwell deduced from his theory that light must exert a pressure; this has been shown to be minute under earthly conditions, but is now believed to reach huge values in the interior of the stars, where it serves to balance the gravitational forces which cause them to contract.

The chief development in connection with radiation has been the discovery of radiations other than light.

As long ago as 1800 Sir F. W. Herschel showed that there is a region beyond the red end of the spectrum where there are invisible rays capable of heating an object exposed to them; two years later it was shown that the region beyond the violet showed rays capable of causing chemical effects. These infra-red and ultra-violet radiations were shown before 1850 to be wave-motions and fully analogous to light.

The development of the spectroscope (*c.* 1860) made the accurate study of these rays more practicable as also did the invention of photography, which became practicable about 1830, was much improved about 1850 and became a commercial industry in the late 'seventies. In passing it must be remarked that hardly any practical discovery has put such a powerful weapon in the hands of science as has photography.

The film industry, as well as the gramophone industry, originated in the fecund brain of T. A. Edison who, in 1889, showed the first motion pictures. The first public projections on the screen date from 1895, but the emergence of the film from the music-hall took place between 1906 and 1912. Synchronisation with sound was accomplished in 1926.

An altogether new field was opened up in 1888 when Hertz, by means of spark discharges, succeeded in generating electro-magnetic waves (now used for radio) having wavelenths 10,000–100,000 times greater than that of light. Hertz showed very clearly that these waves could show reflection, refraction, interference and dispersion like light. The existence of such waves was predictable from Maxwell's theory: it is surprising, indeed, that they were not found earlier. These rays were found to have remarkable powers of travel. Marconi saw their practical value and in 1897 succeeded in sending signals by them for over a distance of 18 miles: in 1901 signals were sent across the Atlantic and wireless telegraphy rapidly developed. The transmission of speech followed. A great step was the invention of the "valve" by Fleming (1904) and its improvement by de Forest (1907).

Radio-telephony was developed about 1907 by Fessenden. The invention of the valve made it a more practical proposition, but it did not become of real value until 1915, when transmission over distances of thousands of miles was achieved in the U.S.A.

Steady improvements led to the possibility of a broadcasting service, which was begun in 1920 with the transmission of gramophone records and amateur performances. By 1925 fifty stations were transmitting: in 1927, two hundred.

The next phase of development in our knowledge of radiation was the discovery in 1895 of the X-rays by Röntgen. X-rays had in fact been produced whenever cathode-rays, discovered in 1879, were experimented with, but had not been noticed. On this occasion a batch of photographic films lying near a discharge tube was

found to be fogged and it was seen that a new radiation must be present. It was not at once obvious that X-rays were of the nature of light, but in the course of a few years it was shown that they were a radiation exactly analogous thereto, but of wavelength about 5,000 times shorter. Very soon after this the gamma-rays of radium were discovered and were proved to be a similar radiation but of wavelength much shorter still. Of recent years the gaps have for the most part been filled and we are acquainted with all electro-magnetic radiations which have wavelengths between 10^6 and 10^{-10} centimetres.

QUANTUM PHYSICS

At the turn of the century, Physics seemed to be a science most logically built up upon the most unassailable principles. The laws of motion set out by Newton and mathematically developed by his successors seemed capable of describing the motion of any body whatever—star or atom. In some cases the technique of mathematical description was lacking but the actual laws seemed never to be at fault. The kinetic theory of gases explained the nature of heat, and on it was based the eminently satisfactory science of thermodynamics. The wave-theory of radiation, as worked out by Clerk Maxwell, gave an admirable description of optics. To the physicist of 1895 a fundamental change in the bases of the science would have seemed incredible.

The quantum theory was introduced because closer study showed that certain experimental observations could not be reconciled with the "classical" Physics of the nineteenth century.

In the first place the classical theory led unavoidably to the conclusion that almost all the energy radiated from a hot body should be of infinitely short wavelength, whereas in fact most of it is light and infra-red radiation. Max Planck studied as others had done, the actual distribution of energy among the different wavelengths of the spectrum, and concluded in 1901 that this could only be explained by assuming a discontinuity—e.g. that the vibrating systems which radiated were to be regarded as having energies which could assume only certain fixed values and not intermediate ones. This assumption, for which the Newtonian mechanics gave no justification whatever, gave a highly satisfactory explanation of the radiation distribution. In 1907, Einstein discovered that another curious phenomenon, the fall in the specific heats of substances when highly cooled, could be explained by Planck's assumptions, and from 1910 onward the quantum theory began to be useful. Experiments on the way in which light caused electrons to be shot out of certain metals could also only be explained if it was assumed that light consisted of a discontinuous stream of particles (photons) or wave-packets.

No very great interest was aroused, however, until in 1913 the Niels Bohr's theory of atomic structure was put forward (p. 241). The quantum theory was here used to explain the reason why an atom which, on experimental evidence clearly consisted of a positive nucleus and a surrounding cloud of negative electrons, could exist at all; for on the classical theory the electrons, if not rotating, would have to fall into the nucleus: if rotating, they would radiate energy at the expense of their velocity, and, as they slowed up, their orbits would narrow until the whole atom had collapsed. The quantum

theory gave a reasonable solution of this difficulty, but, what was more convincing, it enabled Bohr and others to calculate correctly the exact position of all the lines of the hydrogen spectrum, a feat which made the deepest impression on the scientific world. Accordingly from about 1920 the quantum theory has been accepted as an essential part of Physics. Essentially it states that the interchange of energy between matter and radiation is always by single complete quanta of Energy E, defined by the relation $E = h\nu$ where ν is the frequency of the radiation and h is a universal constant. This seems somewhat remote from everyday physics. But the implications of this theory are enormous. The chief of them perhaps is the notion of indeterminacy, introduced by Heisenberg (1925). If a minute particle, e.g. an electron, is to be detected, it must indicate its position somehow: this can only be done by some interaction with at least a single quantum of energy; but gain or loss of this quantity of energy is in itself enough to disturb profoundly the velocity or position of the particle we wish to observe. Consequently we cannot define exactly the state of a very minute particle. Born and Heisenberg in 1925 introduced quantum-mechanics, a science devoted to describing the motion of minute particles. It works admirably, but does so at the cost of rejecting all hope of forming an intelligible picture of the motions. In quantum-mechanics we have to assume an object to be both a wave and a particle: moreover we have to assume that an electron may be in two places at once. It is not necessary or possible to visualise this, and the need to do so is no longer felt. The tendency of Physics to-day is no longer to provide an intelligible view of the world. In the words of Dirac, "The only object of theoretical physics is to

calculate results that can be compared with experiment and it is quite unnecessary that any satisfying description of the whole course of the phenomenon should be given."

It is small wonder that the new Physics seems unfamiliar. Throughout our whole individual and racial lives we have derived our personal and human method of thought from observation of masses of matter, enormously larger than the ultimate particles and very naturally our habit of thought cannot conform to their behaviour. We are reaching the new conception that what is inconceivable is not therefore the less likely to be true, if our standard of truth is the correspondence of experimental results with prediction.

The historian of science must be cautious in assessing the value of recent theories. Whether the quantum theory survives or whether the classical, quantal and relativistic views become merged in a single Physics (as it is the effort of many to merge them) the historian will see the year 1900 as marking the discovery of the insufficiency of the fundamental laws of motion, on which, for more than two hundred years, science had built its whole theoretical structure. The greater part of that structure remains unaltered, for the quantum theory differs from the classical theory only where the motions of individual minute particles, such as atoms or electrons, are concerned: aggregations of billions of these, such as we encounter in the older Physics, conform to the classical Newtonian concepts.

The quantum theory must be thought of not as destroying, but as amplifying, the classical world-view.

BIOLOGY—STRUCTURE OF ANIMALS AND PLANTS; PROGRESS SINCE 1850

By 1850 human anatomy had been worked out in its main outlines; none the less since that time many thousands of papers have been contributed on its finer details, especially the microscopic anatomy of such complex organs as the brain and spinal cord.

The anatomy of animals has also been enormously developed, as the comparison of the anatomy of different species is one of the chief sources of evidence bearing on the theory of Evolution (p. 278). The anatomy of plants was also almost entirely worked out between 1840 and 1880.

The characteristic advance in our knowledge of the structure of living creatures has been the discovery and study of the cell as the unit of living matter. The microscopists of the seventeenth and eighteenth centuries had seen that plant tissues were in part built up of cells. The botanist Schleiden in 1838 formulated the theory that plant tissues were composed entirely of such cells, conceived by him as vesicles with a solid wall and fluid contents. Schwann in 1839 extended the theory to animal tissues and showed how the simple embryonic cell differentiates itself into the very various kinds of cell which make up skin, gland, muscle, nervous tissue, etc. The cell-nucleus had been noticed by the botanist Brown, but it was Schwann and Schleiden that realised it was an important part of the cell. Nevertheless they regarded the cell-wall as the most important feature and did not so much interest themselves in its contents. The great plant-anatomist, von Mohl, drew attention to the jelly-

like cell contents, which he named *protoplasm*, and noticed its streaming movements. He opposed the view, advanced by Schwann and Schleiden, that cells could be formed from a liquid medium as a crystal from a solution; this point was settled by Virchow, who in 1858 laid down the law that every cell originates from another cell. Meanwhile the notion of the cell as a closed vessel was vanishing. Schultze (1863) made it clear that the cell-wall was by no means essential, and that a cell was, in fact, a little mass of protoplasm containing a nucleus. The cells, it was seen, were not isolated; for bridges of protoplasm passed from one to the other. The cellular theory of living things was at its height in the 'seventies and 'eighties and like all great theories was overstressed. The essential balance and unity of the organism were overlooked in its analysis into units; the rise of Physiology, which is essentially a study of the way in which an organism co-operates in all its parts to keep its internal environment constant, served to correct this.

The division of cells to form new cells was much studied in the 'seventies and 'eighties. It became clear that the cell was by no means a lump of structureless jelly, but contained numerous structures so minute as to be at the limit of visibility. The protoplasm was seen to be full of minute granules and to have a foam-like structure (Bütschli, 1892). Microscopic examination of this has not proved very fruitful. The study of the nucleus has, however, led to most remarkable progress in the field of heredity, a subject taken up again on p. 275.

The cell still holds for us the essential problems of life. It has the fundamental properties of living things—irritability, assimilation, reproduction. The explanation of the chemical and physical mechanism by which its

functions are performed is largely lacking even to-day. The solution of the problem of the nature of the small-scale processes in the cell could not solve for us by any means all the problems of Biology, for the organism is much more than the sum-total of its cells; but while the working of the unit of life is not understood, biological science must remain incomplete.

PHYSIOLOGY OF PLANTS AND ANIMALS; PROGRESS SINCE 1850

Physiology, the study of the life-processes by which plants and animals feed, excrete, breathe, grow, perceive and move, by which in short they maintain themselves as enduring entities in a changing environment, has been created from mere rudiments since 1850.

This is particularly true of the Physiology of plants. A few facts were known in the eighteenth century. The movements and pressure of sap and the importance of light had been studied by Stephen Hales (1727). Later it was shown plants absorbed carbon dioxide and emitted oxygen. But systematic study of the working of plants belongs to the nineteenth century and is due, more than to any other man, to Julius Sachs (1832–97) whose great text-book of botanical physiology was published in 1865.

Most of the problems of plant-life are as yet but partially solved. The first of these for consideration is the manner in which the root takes up water from the soil and the way in which this water is forced up the vessels of the stem to the leaf. De Candolle (1778–1841) worked out the phenomenon of osmosis by which the liquid contents of the root-cells tends to dilute itself by drawing in water

from without, so creating a pressure in the cell which could force the liquid upwards. But these forces seemed too small to account for water travelling to the tops of trees, and in 1876 the idea was reached that evaporation of moisture from the leaf drew a water-column up through the narrow vessels. That the column could reach greater heights than 32 feet (p. 145) was explained by the fact that an unbroken thread of water needs considerable force to break it. The loss of water from the leaf (transpiration) and the way in which this is regulated by opening and closing of the leaf-pores were investigated between 1858 and the end of the century; the exact mechanism is not fully understood as yet.

This opening and closing was the first example of a motive response of plants to changes in their environment. It had long been known that plant-stems sought the light and that roots grew downward and shoots upward; these responses were studied by Charles Darwin and his son Francis Darwin. They showed that in many cases one part of the plant, e.g. the tip of the shoot or root, might receive the stimulus of light or gravity while another part actually moved in response to it. These experiments suggested some sort of nervous mechanism, but early in the twentieth century it was shown that the stimulus caused a growth-promoting substance to be formed and that this diffused from one cell to another and finally caused more rapid growth on one side of the shoot and thus made it bend. In the last few years these substances have been isolated and have been shown to be quite simple chemicals.

The feeding of plants was only slowly elucidated. The "humus" theory prevailed at the beginning of the century, plants being supposed to derive their nourishment, at least

in part, from the decayed organic matter in the soil. It was known in the late eighteenth century that plants could absorb carbon dioxide and give out oxygen: Liebig (p. 247) realised that the carbon dioxide came from the air, not from the soil. Dutrochet (1776–1847) proved that it was only the green portions of the plant that could perform this function. Von Mohl (p. 263) noticed that starch grains were often associated with the green bodies (chloroplasts) in the plant cell. It was Sachs, once more, who realised that the green substance, chlorophyll, was a necessary factor and that the production of starch and sugar could only occur in light. From 1864 on, it was shown that the green pigment by itself was ineffective and that only in conjunction with the colourless (or pink) plastid could starch be formed. Sachs suggested that starch was formed directly: the modern view is that carbon dioxide and water yield a simple sugar and oxygen, and that the sugar is then converted into starch. Sachs showed too, that the starch after its formation was converted into sugar and could travel as such in the sap. Mayer in 1885–6 made it clear that starch deposited in the plant (as in a wheat-grain or a potato) was a reserve food material. The notion that such chemical changes in the plant as are not readily paralleled in the laboratory, are brought about by enzymes (organic catalysts) is quite an old one, dating back to 1833, when a study was made of the conversion of the starch of barley into malt-sugar. These enzymes have been much studied, and it would seem that they can cause the building of complex compounds as well as their breakdown.

The plant requires nitrogen compounds. Up to 1860 it was thought that it absorbed complicated organic nitrogen compounds from decayed vegetation (humus) in

the soil, but Boussingault, about 1860, disproved this. Berthelot studied the question between 1876 and 1892 and showed that plants assimilated their nitrogen as inorganic nitrogen (nitrates). He showed that these arose through the action of lightning and rain on the air, and that certain bacteria in the soil could absorb nitrogen from the air and convert it into a form which plants could use. Winogradsky and other workers in the 'eighties and 'nineties investigated these bacteria and showed that the nitrogen of dead animals and plants, and other products was converted by them into nitrates and nitrites which the plant could use. Thus were laid the foundations of the great conception of the balance of life (p. 281).

The breathing of plants was not well understood before the 'sixties. In the second quarter of the century it was thought that a plant took in carbon dioxide and emitted oxygen during the day, but that at night, like an animal, it took in oxygen and breathed out carbon dioxide. Sachs in 1868 showed that this was not true; that every living cell had to respire, i.e. to absorb oxygen and to expel carbon dioxide: that respiration was continuous, but that the conversion of carbon dioxide and water into starch and oxygen took place only in the light and was wholly separate from respiration. The recognition about this time that the processes of the plant and animal cell were essentially similar was one of the great unifications of the biological world. The respiratory changes in the cell have been shown to be very complex. The change

Sugar + Oxygen → Carbon dioxide + Water + Energy

is a summary of them, but many stages are certainly involved.

The tendency in plant and animal physiology alike is to realise that an organism is not a static object nor an

assemblage of parts. It is a Whole, in dynamic equilibrium, taking in and giving out both matter and energy and correlating the action of its organs in such a way as to preserve its internal environment unchanged despite changes in the outer world.

The science of Animal Physiology has developed out of all recognition since 1850. The functions of the body may be grouped as (*i*) those taking place within the cell, (*ii*) the system for bringing nutriment and oxygen to the cell *via* the blood and for removal of waste products and carbon dioxide by the same agency, (*iii*) the co-ordination and control of bodily functions by nervous impulses and hormonic stimuli.

The cell processes of animals still remain on the whole obscure. As in the plant-cell, sugar and oxygen (both derived from the blood) combine in some complex manner and ultimately give carbon dioxide, water and energy. Of recent years it has been proved that intermediary substances (e.g. glutathione, discovered by Gowland Hopkins in 1921) take part in the oxidation, that phosphates are necessary, and that lactic acid is formed and in some manner removed. But on account of the minute scale of the cell-processes not a great deal has been discovered about them.

The function of the blood as food-bringer must include the physiology of digestion. We may note here first the researches of Beaumont (1833) who had a patient, with an opening into his stomach, by study of whom he obtained much information as to the gastric juice. In 1846 the great French physiologist Claude Bernard discovered the fact that the pancreas produced ferments which could digest all types of food. Bernard discovered the power of the liver to store sugar as "glycogen," a sort of starch, and

so showed that the body can build up compounds as well as break them down. Succeeding years showed progress in the understanding of digestion. The ferment secreted by the small intestine itself was discovered in 1901 and about this period the control of digestion by nervous action and by hormones was worked out. The discovery in 1922 of insulin, the catalyst which causes sugar to be utilised in the blood and which is ineffective in diabetes, marked a new era. It became clear that a delicate balance was preserved whereby there was always a certain small proportion of sugar in the blood available for the cell-processes, this being replenished from the store of glycogen in the liver. From 1911 it has been known that minute quantities of certain substances—vitamins—are required in addition to the diet of protein, carbohydrate and fat: their mode of action is still obscure.

Metabolism, that is the manner in which the body transforms foodstuffs into waste products and energy, has been widely studied. This has been done by measuring the oxygen used up and carbon dioxide evolved by gas analysis. The study of the gas-exchange of the body is due chiefly to Ludwig and Pflüger (1872), who first extracted the gases from blood and analysed them; later to J. S. Haldane (1892 onward), Douglas, Barcroft and others. The rate of working of the body was also studied by enclosing the whole body in a heat-proof box and measuring the energy it gave out as heat.

The control of the circulation of the blood was first studied by Bernard, who in 1851 discovered that the blood-vessels were dilated or constricted by a nervous mechanism which thus controlled the blood supply to a particular part. Ludwig (*c.* 1870) developed the study of the rate of blood flow.

Much work has been done since the eighteen-nineties on the heart and its peculiar type of nervous control. By mapping out the minute electric currents which its action induces an elaborate wave-tracing (electrocardiogram) can be obtained showing clearly any irregularity in its action.

The removal by the kidneys of waste products and excess water proved an interesting study. The earliest view, that of Ludwig, was that the blood pressure forced the watery portion of the blood through a filtering membrane, but, like so many other purely mechanical explanations, it had to be given up when further experiments showed that injection of urea into the blood caused more rapid secretion of urine, but no change of blood pressure. These studies have been greatly refined and the regulation of the water and salt content of the body has been worked out in this century by Cushny and others.

The protective functions of the blood have been greatly studied. Metchnikoff in 1884 showed that the white-cells of the blood engulfed and destroyed disease germs: but this is but a small part of its power. In 1890 von Behring discovered that the blood contained substances which destroyed both disease germs and the poisons they produced. This very intricate subject of immunology has been worked out by Ehrlich, Topley and others.

The co-ordination of the various organs of the body has been widely studied. The nerves are the obvious system of intercommunication: but, in common with protozoa and plants which have no nervous system, the higher animals also regulate their workings by sending out chemical substances (from ductless glands) and thus influencing distant organs. Thus, for example, the ovary at puberty sends into the blood-stream a hormone which

causes the enlargement of the breasts and growth of hair on the body.

The elucidation of the nervous system has attracted a host of workers. Among the earliest of the modern period were Magendie and also Flourens in France (*c.* 1820) who investigated the function of the cerebellum—a part of the brain chiefly concerned with co-ordination of movements. The latter also demonstrated the functions of the semi-circular canals of the ear, which are the organs by which we judge of our position in space. Marshall Hall in 1833 discovered the *reflex,* the method by which a stimulus produces a response apart from sensation or volition.

Johannes Muller about 1840 put forward the very important doctrine of specific nerve energies. Each nerve, he showed, carried a particular type of sensation and no other. Thus the auditory nerve could convey only the impression of sound, the optic nerve that of light, no matter whether they were stimulated by pressure, heat, electricity, etc. Helmholtz (p. 250) between 1856 and 1866 made further investigation into the senses of sight and hearing.

From 1850 onward the nature and course of the nerve fibres received attention. Waller, and later Golgi, showed that the long fibres which carry the impulses were each prolongations of a nerve-cell, and Cajal and others have worked out with a good deal of accuracy the way in which these cells and their tree-like processes are associated in the brain. The first proof that certain parts of the brain are associated with certain organs and functions was due to Broca, who discovered the speech-centre in 1861. Fritsch and Hitzig in 1870 worked this out in more detail. The respective functions of the brain and spinal cord were worked out by Goltz in the years 1869–96. He removed

the brain from frogs and dogs and showed that most of the bodily functions could continue and therefore were conducted by the spinal cord. Such animals, however, had none of the higher functions and could not regulate their conduct to avoid injury. On the other hand, animals from which the spinal cords were removed appeared to retain their mental functions but were paralysed. The very complex system of reflexes by which even simple acts are performed has been investigated by Sherrington in the years 1896 onward. The tremendous complexity of the structure of the brain is at least adequate to the complex tasks it performs. Almost nothing is as yet known about its higher functions, probably operated by the front part of the brain, but a good deal is understood as to the parts of it which control the fulfilment of particular bodily functions.

The process of fertilisation in animals has been the subject of continual conjecture in all ages. No real evidence as to the function of spermatozoa was advanced until in the early nineteenth century it was shown that semen devoid of these or from which they had been removed by filtration could not cause fertilisation. The actual process of fertilisation, the entry of the active spermatozoon into the female ovum, was first observed in 1855 in a fresh-water alga. It was only in 1879 that the process was first observed in an animal (a starfish, *Asterias Glacialis*). At this date, then, it was established that the spermatozoon from the male entered the ovum of the female. The nuclei of the two cells were seen to fuse and the process of development of the embryo by the splitting of the fused cell into 2, 4, 8, 16, 32 and more cells to begin. The formation and uniting of the male and female elements contain the mechanism of heredity,

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which has been much elucidated of recent years. Of great interest is the work of Hertwig (1896) and Loeb (1899 onward) in causing the unfertilised eggs of sea-urchins to develop by treating them with certain solutions or even by pricking them with a fine needle.

The process of the development of the embryo has always been of great interest. The development of the chick in the egg received especial attention from the time of Aristotle, but in the seventeenth and early eighteenth centuries research was discouraged by the doctrine that the embryo was a "preformed" adult. In the later eighteenth century it was realised that the organs were not "ready-made," but differentiated themselves from undifferentiated tissue. The anatomy of the human fœtus had been very carefully studied by William and John Hunter and this was highly developed by the beginning of the nineteenth century. Much less was known of the earlier stages of development. In 1817 the Russian naturalist Pander observed that the chick developed from three layers of substance and showed how the organs were formed from these. Von Baer in the 'twenties extended these notions. He also discovered that mammals originated from a true though very minute egg. Moreover he showed that the embryos of such very different creatures as reptiles, birds and mammals were at an early stage hardly distinguishable. This was taken up by Haeckel, who in 1866 made much of the notion that the development of the individual recapitulates that of the race. After the discovery of the cellular structure of animals the development of the organs from the three layers was worked out in more exact detail, but it was only in the 'fifties and 'sixties that the view that the egg was a simple cell attained clear expression and the early development

of the embryo was worked out. Kowalewsky in the years 1866–77 worked out the development of Amphioxus, the lancelet, from the egg-cell with great exactness. This work was observational, but in the last fifty years experimental embryology has been founded. Driesch showed that after the primitive egg had divided into two, four, eight, sixteen and even thirty-two cells each of these, if separated, retained the power to develop as a whole embryo. Recent work has shown the existence of an "organising centre" in the young embryo which causes certain cells to form certain organs.

The fertilisation of plants was well studied in the late eighteenth century; the pollen was conceived of as the male element and the ovule as the female. Amici in the eighteen-twenties saw the pollen tube given off by the pollen grain and even observed a pollen tube to enter an ovule. In 1846 Amici demonstrated quite clearly that something in the pollen tube caused the egg-cell in the ovule to develop into an embryo. The non-flowering plants were investigated without much success until Hofmeister between 1849 and 1860 worked out their life histories and showed that one great plan, "the alternation of generations," governed the reproduction of all plants.

The mechanism of heredity has been much cleared up in recent years. The first scientific theory of heredity was that of Darwin (1866), who supposed that the various organs of an individual were represented by particles which had the power of reproducing the organ in question and that these particles passed from parent to offspring in the sperm and ovum. This theory was of no great value, but it was an attempt to give a physical explanation. The next important influence was that of Weismann. In 1889 he pointed out that the germ-cells alone continued as a

continuous stream of life from one generation to another. All the cells in a living body are direct descendants of the fertilised ovum from which it sprang. All these cells will perish except those which the body hands on to its own offspring. The germ-plasm which constitutes these few cells—the only continuous factor in the race—was, then, the vehicle of heredity.

Meanwhile Mendel in 1866 and 1869 had published papers on the inheritance of various characters in peas. They attracted little or no attention, as being out of the general current of scientific thought. Their thesis was that each inheritable characteristic in an organism was represented by *two* factors, of which *one* passes to its offspring. Thus if a pea plant which grows tall has factors TT, and a pea that grows short, SS, then the offspring of the two would have both factors, TS. If two of these offspring were crossed we should obtain with equal probability the types TT, TS, ST, (identical with the last) and SS. Where more characters than one are considered the matter becomes more complex.

Meanwhile it had been found that when sperms and ova were formed in the parental body, certain bodies called chromosomes behaved like these factors, i.e. they divided into *two* and only *one* half passed to the offspring as a sperm or ovum. It became clear in the years following 1910 that these chromosomes contained the hereditary factors of Mendel. The hereditary factors are to be numbered in thousands and of chromosomes in tens, so clearly many factors reside in each chromosome. Hypothetical bodies called *genes* have been assumed to be contained in the chromosomes and to carry the Mendelian factors. Moreover, microscopic examination of the chromosomes at certain stages has indicated very recently

that they are built up of rings or discs of which one or more correspond to each gene.

The working out of the gene-theory is due largely to T. H. Morgan, who has made a most exhaustive study of thousands of generations of the fruit-fly, *Drosophila*, in the years 1910 onwards.

We have, of course, no idea at all as to how a gene, which from its minute size cannot be a very complex structure, can transmit a hereditary character.

THE RELATION BETWEEN SPECIES

That there were relationships between individual species was, of course, recognised by the earliest authors who attempted to classify them. In the eighteenth century two tendencies were apparent. A more scientific classification of species was made, especially by Linnaeus, while prominence was given to the philosophic notion of a "ladder of life," on which all organisms, from the simplest living things up to Man, could be placed in a scale of increasing complexity. Cuvier upset this doctrine by his exact study of the anatomy of animals. He saw (1817) that there was no ladder of nature but that the animal kingdom constituted four groups or *embranchements* which may be termed:—

1. *Vertebrata,* animals with backbones.
2. *Mollusca,* snails, cuttlefishes, etc.
3. *Articulata,* or jointed animals, e.g. insects, etc.
4. *Radiata,* including all other animals.

This last group is a "mixed bag," but the other three constitute a good grouping.

Each of these groups is built on a different fundamental plan. Cuvier perceived the remarkable likeness of plan which marked out species of the same group, but he believed that species were quite fixed and unalterable.

Cuvier's studies of comparative anatomy were monumental, and he took the great step of uniting in the same classification fossil and living forms. The extinction and appearance of new species were explained by him as the consequence of a series of violent world-catastrophes which extinguished many forms; the world, he supposed, was re-peopled from the survivors. His followers supposed a new creation to follow each such catastrophe.

Meanwhile the study of Geology had proceeded, and Lyell (*c.* 1830) made it clear that the strata in which fossils were found had been laid down slowly by deposition from seas and rivers to-day, and that there was no evidence of the catastrophes of Cuvier. The theological difficulties attendant on these views have already been mentioned.

Richard Owen carried the study of comparative anatomy still further than Cuvier, and gradually there was built up an ever more accurate picture of the likenesses and differences of species and the natural groupings into which they fell.

The greatest step of the nineteenth century was the notion of Evolution, primarily due to Charles Darwin. The idea that species were not immutable, but might have evolved one from another, had been many times suggested. Darwin's own grandfather had made the suggestion, and it had been carried further by Lamarck (p. 202). Lamarck believed that a species modified itself by its own striving. The use of an organ led to its increased development, and this development, he supposed, was handed on to its progeny. Thus the giraffe, he supposed, had been evolved

from some form of antelope which lived on tree-shoots and stretched to reach the higher branches. By so doing it caused its neck to grow slightly longer, and this increase would be handed on to its offspring, who would further modify their own necks. This view involves the inheritance of acquired characters and this stands in the way of its acceptance, for such inheritance has never been satisfactorily proved. Lamarck's hypothesis has always been attractive to philosophers in that it introduces the idea of a purpose in living things which causes their evolution to higher forms.

But Darwin's contribution was so much greater than any of the earlier ones because he presented not a mere theory, but a theory supported by a mass of unassailable fact. He approached the whole question with infinite care and caution, and considered the theory for twenty years before he made it public. His theory of Evolution may be best summarised in the words of Huxley:

"All *species* have been produced by the development of *varieties* from common stocks by the conversion of these, first into *permanent races* and then into *new species,* by the process of *natural selection,* which process is essentially identical with that of artificial selection by which man has originated the races of domestic animals—the *struggle for existence* taking the place of man, and exerting, in the case of natural selection, that selective action which he performs in artificial selection."

Darwin had arrived at this idea by 1839, though as early as 1836 he had come to doubt the immutability of species. At this time he visited the Galapagos Islands off the coast of South America and noted that each island had its own species of animals which, though distinct, resembled each other and the fauna of the mainland. It

seemed incredible that all these were unrelated, and more likely that they had arisen by different modifications of the same original types on the different islands. But how was this modification caused?

The idea of natural selection arose in Darwin's mind in 1839, and he continued until 1858 to develop the evidence for the theory. In that year a young naturalist, Alfred Russel Wallace, came independently to the same conclusions and sent a sketch of the theory to Darwin. Much to their credit the authors made no disputes about priority, but published a joint paper in 1858. Darwin's great work, *The Origin of Species,* followed in 1859. The reception of the book and its philosophic influences have already been discussed (pp. 234–6). Its influence on Biology has been overwhelming. It at once provided a rational means of classification. A classification correctly based on Evolution would represent not merely an arrangement of species in groups derived from the exercise of a biologist's fancy, but would place in each group species which had evolved from a common ancestry. The theory had proved also to be the rational basis for the study of fossil forms of life.

Darwin's view of the mechanism of evolution was by no means unchallenged, and the views held to-day are by no means identical with those expressed in *The Origin of Species.* Darwin supposed that a species was always undergoing minute variations, that some of these were favourable to the survival of the species and some unfavourable; that the struggle for existence eliminates a great part of the individuals before they have the opportunity to multiply, and that those which had variations favourable to survival would be enabled to breed, and would transmit their favourable variations to their offspring.

This mechanism was doubted, chiefly on the grounds

that very small variations could not give their possessors sufficient advantage to cause their preferential survival.

The discovery of the laws of heredity has placed the evolutionary theory on a new basis. There is no evidence that any character which does not affect the chromosomes and genes (p. 276) of the cell nucleus can be inherited: but it has also been shown that at intervals alterations in the genes do occur and that such alterations can be inherited. The neo-Darwinian point of view now generally held differs from that of Darwin chiefly in its definite denial of the inheritance of acquired characters and in its realisation that quite large variations may occur and be inherited on Mendelian lines.

THE INTERDEPENDENCE OF ANIMALS AND PLANTS

The conception of the interdependence of the animal and plant worlds developed but slowly. The idea that the plant obtained its carbon from the carbon dioxide of the air dated from 1840: that its nitrogen was obtained from soil nitrates resulting from bacterial action was not cleared up until the 'eighties. It was about this date, then, that the great generalisation of the mutual dependence of green plant, bacterium and animal fully emerged. It then became clear that the green plant alone could take carbon dioxide from the air to build its tissues: which tissues either were eaten by higher animals or decayed (i.e. were eaten by bacteria). The animals or bacteria returned the carbon of these plant tissues to the air in the form of the carbon dioxide exhaled in their respiration.

Thus all living matter was dependent for its existence on the green plant. The nitrogen which the plant

required to build its proteins is taken from soil-nitrates. The plant proteins are eaten by higher animals or bacteria and converted into animal proteins. All the substance of the animal ultimately returns to the soil, where bacteria convert its proteins, etc., into nitrates which the plant can use once more.

This conception of the whole living creation as biologically dependent is perhaps the most general development of the interrelation of species. In the last eighty years, however, the mutual dependence of smaller groups has been studied.

THE INTERDEPENDENCE OF SPECIES

The discovery of new species and their habitat was among the earliest of biological pursuits. It has proceeded apace, and it is thought that about half a million species of animals and plants have been described and named. A newer department is the study of organisms with relation to their natural environment—known as Ecology. The term was invented by Haeckel in 1869, but its development as a science is quite recent. Its most interesting aspect lies in the dependence of species on each other, which often has a very practical value for man. Thus the commercial growing of sugar-cane in Hawaii was successful until the closing years of last century, when the sugar-cane leaf-hopper was introduced from Australia. In Australia there were other species which prey on it: in Hawaii there were not, and consequently it increased beyond all bounds and reduced the sugar-cane crop to little more than one-third of its previous value. It was discovered that a minute wasp and also a Capsid bug

preyed on the leaf-hopper. These were introduced into Hawaii; the balance of species was restored and the population of leaf-hoppers now stays at a low level. The study of the closer dependence of species—parasitism and symbiosis—has proved of equal interest. Ecology in the animal world is chiefly the study of the effect of the law "eat or be eaten"; in the plant world, factors of non-living origin—soil and climate—have great importance. The predominance and even the existence of a plant depends on its being able to obtain a sufficient share of light, air, water and mineral salts, and to produce and disperse its seeds or spores.

The notion of the living world as a balanced unity of interdependent individuals is fundamental to our world-view and is, at any rate in its scientific study, the product of the last half-century.

BACTERIA AND DISEASE

The transfiguration of Medicine and Surgery which has occurred during the last three-quarters of a century has been brought about by numerous and brilliant pieces of research. But one discovery towers above the rest, namely, Pasteur's discovery of the bacterial origin of disease. From this developed three great branches: systematic preventive Medicine: antiseptic and aseptic Surgery: and the treatment of disease by vaccines, sera, antitoxins, etc. Louis Pasteur was not a medical man but a chemist. He was born in 1822, and in 1854 became professor of Chemistry at Lille and there studied fermentation. It had long been known that fermentation was always accompanied by growth of yeast, and putrefaction by the

growth of bacteria. Pasteur became convinced that fermentation and putrefaction were changes brought about by these living creatures; this was in contradiction of the usual view, which was that putrefaction was a chemical process independent of life and that the bacteria were generated by the process of putrefaction. The idea that animals could arise spontaneously from non-living matter was an ancient and persistent one. A frequent explanation of the first creation of living things—at least among non-Christian philosophers—was that they were generated from mud or slime. Aristotle taught that plant-lice were bred from dew, and that maggots arose spontaneously from putrid flesh. As late as the seventeenth century we find authors asserting that such high organisms as mice were generated from mud or from dirty linen. Such notions gradually became less credible. In 1668 Redi proved that putrid meat, screened from flies by wire gauze, bred no maggots and that these were produced only from the eggs of flies. It still remained credible, however, that bacteria and infusoria might arise from non-living matter. Pasteur exposed putrescible liquids, such as broth, to air from which all suspended matter had been filtered. The broth did not putrefy. By such experiments, carried out in 1861, he proved to the satisfaction of the scientific world in general, that his view was correct, that these living organisms were not spontaneously generated, and that putrefaction occurred only through the growth of bacteria.

The notion that diseases might be due to infestation by minute organisms had been suggested, but had received little favour. In 1862 Pasteur, investigating a silkworm disease which was ruining the French silk industry, showed this to be associated with microscopic organisms. Ten

years later a spirillum was observed in the blood of a relapsing fever case, and in 1875 parasitic amoebæ were found to cause a certain type of dysentery. But the first accurate knowledge of the bacterial origin of an infectious disease of a higher animal we owe to Robert Koch, who in 1876 demonstrated that the deadly disease of anthrax, which affects men and other mammal, was due to the growth of a bacillus in the individual affected. Koch investigated the life-history of the bacillus and showed how it brought about infection. He also discovered the method of growing the bacilli in blood-serum outside the body and the technique of staining them with dyes and so making them readily visible. He thus laid the foundations of the science of bacteriology. Once the technique of studying bacteria had been discovered, rapid progress was made and the bacterial origin of many diseases was discovered.

But many years before exact knowledge of the causation of disease by bacteria was reached, a practical mastery over it was gained. The knowledge that epidemic disease could be transmitted by contaminated water anticipated the knowledge that it was the bacteria contained therein that caused its deadliness. Lord Lister, too, was led by Pasteur's early work to realise that the infection of wounds was akin to putrefaction and therefore brought about by bacteria. This realisation was enough to enable him to derive and apply the principles of antiseptic Surgery at a date thirteen years before the discovery of the streptococcus and staphylococcus, which cause wounds to become septic.

PREVENTIVE MEDICINE

One of the most important results of the scientific work of the nineteenth century was the establishment of a system of preventive Medicine.

The notion that the health of the people should be in the direct care of the State was slow to develop. Disease was widely regarded as an unavoidable calamity, because its causes, direct and ultimate, were almost unknown. Attempts to exclude foreign epidemics by quarantine had been made from early times, but these were rarely of use.

In the early nineteenth century a certain philanthropic spirit had begun to grow and the first steps towards public health were attempts to improve the conditions of labour. Factories were at this time utterly uncontrolled, and consequently the lot of the workers, many of whom were mere children, was arduous, unhealthy and oppressive. Some public assistance was also given towards vaccination but otherwise the State did nothing for the health of its members.

The labours of Edwin Chadwick in England led to enormous improvements in public health, by awakening the public mind to a sense of sanitation. The crude sewage-disposal of the villages had progressed little since the Middle Ages. In sparsely populated areas this was tolerable: the growth of large towns without sewerage, and with inadequate and unclean water-supplies caused a death-rate which to-day would be thought appropriate to a pestilence. England before 1850 was incredibly filthy. The water-closet is quite an ancient invention; it was not, however, until about 1830 onward that it began to be in general use in the houses even of gentlefolk, for in a great

part of the country there was neither public water-supply nor public sewers. At worst the filth might be allowed to accumulate in the streets into vast middens containing a hundred tons of ordure; it might be conducted away by an open stinking ditch, perhaps into a local stream or pond. It might enter a cesspool, often beneath the kitchen floor, and thence soak into the soil. Supplies of water, usually unfiltered, were available for the better houses in the bigger towns, but pumps and wells were the main standby. These wells were usually shallow and were likely to be contaminated by filth soaking through the soil or flowing over its surface. The water-borne diseases of cholera and especially typhoid fever (then spoken of as typhus or merely as "fever")[1] took a fearful toll. About a twelfth of the British population were certified as dying of "fever"; the present proportion is about one five-hundredth. About 1830 there swept over Europe a wave of the deadly Asiatic Cholera—a disease which we now know to be ordinarily acquired by drinking water which has been contaminated by the excreta of a cholera patient and therefore contains the bacterium which causes this disease. A mortality resulted comparable with that from some of the great plagues. England was more lightly affected than some countries, but even here the epidemic served further to emphasise the urgency of some preventive measure.

A landmark of progress was the *General Report on the Sanitary Condition of the Labouring Classes*, published in 1842, which proved very clearly the connection between "fever" and filth, and laid bare a picture to revolt the strongest stomach. This report was instrumental in bringing about

[1] Typhus fever conveyed by lice, relapsing fever due to a filter-passing virus and typhoid fever due to a water-borne bacillus were not distinguished till *c.* 1850. The last probably produced the greatest number of casualties.

improved drainage, but the chief mode of contagion remained unknown. All the medical men believed that the cause of the disease was the gases and odour arising from the filth and hardly any attention was paid to the contaminated water-supplies. The cholera epidemic of 1854 afforded Dr. John Snow the opportunity of proving the suggestion which he had made in 1849 to the effect that the water-supply was the means of conveying cholera. A violent outbreak of cholera occurred in one small district of London—near Golden Square. Snow showed that all the cases were in the habit of drinking the water from the pump in Broad Street, that cases occurring even at a distance had taken the water—one lady sent for it daily from Hampstead—and that those that drank no water from that source were unaffected.

Such facts as these began to rouse the public to the notion of an intimate connection between illness, filth and bad water. The explanation had to wait for the discovery of the relation between bacteria and disease arising out of the work of Pasteur, Koch and others (pp. 285, 295). Cesspools, in towns at least, were gradually replaced by sewers, and in the course of time the standard of purity of water supplies became higher.

In most countries of the world there gradually arose a conscience as to health. First came the notion that epidemic and endemic diseases were in many cases preventable. Then came the stage of legislation. In England medical officers of health were first appointed in 1847; by 1875 every local authority, urban or rural, was compelled to appoint one. In 1848 a Board of Health was formed which made itself exceedingly unpopular by urging elementary sanitary reforms for which the public was not ready. Various Public Health Acts made it

possible for local authorities to enforce certain measures of cleanliness and hygiene; then, more slowly, legislation enabled the Government to force the less willing authorities to put their houses in order. These measures gradually brought about the modern sanitary system by which water practically free from disease-producing bacteria is supplied and by which no unfiltered sewage is allowed to enter rivers. These two measures have practically abolished cholera and reduced typhoid fever to about one-twentieth of its former incidence. The provision of an ample water-supply has greatly increased personal cleanliness: the louse is now uncommon in civilised countries; consequently the deadly typhus fever, the virus of which it may carry, has also almost disappeared.

The gradual conquest of tropical disease is the second triumph of preventive Medicine. Malaria used at one time to cause a higher sickness and death-rate than any other disease. The malaria parasite was discovered by Laveran in 1880 and its life-cycle worked out by several Italian workers. In 1897–1899 Ronald Ross, in India, made the essential discovery that the parasite was carried from one patient to another by the bites of mosquitoes infected with the disease.

This discovery showed the means of prevention. The mosquito larva lives in water and breathes through a fine tail which is brought to the surface. By covering pools with a film of oil and by keeping fish in open tanks, etc., the mosquito could be exterminated. Such means as these with the use of mosquito-netting and of mosquito-proof houses have proved successful in greatly diminishing the mortality.

The deadly yellow-fever has been shown to be transmitted by mosquitoes, and by controlling these some of

the plague-spots of the world have been rendered healthy.

The prevention of other diseases has also been made a public matter. More and more fever hospitals were gradually established, and in 1889–90 the notification of certain infectious diseases was made compulsory. This has been further extended by subsequent legislation.

In the nineteenth century the tendency of Government action was to preserve the community from epidemics; no such public concern was felt for the health of the individual. The twentieth century has seen much legislation directed to the end of ensuring health for the individual. The National Health Insurance Act, 1911, and the medical inspection of school children, are the two greatest steps; the first provides every worker with medical attention; the second sees that no child grows up without such aids to health as the public services can give. The formation of a Ministry of Health in 1919 symbolises the State's direct concern with the health of the individual, and the existence of disease preventable by legislative action is felt to-day to be a crying scandal; so far have we travelled in a hundred years.

None the less we cannot be wholly satisfied. Public Health services can only go as far as public education will allow, and an awakened sense of the community's responsibility for disease is quickly followed by action. When we reflect that in a recent year the number of children who died in their first year was thirty-eight per thousand in Canterbury and ninety-eight per thousand in Barrow-in-Furness, we begin to see where there is room for future progress.

SURGERY SINCE 1850

The two greatest events of surgical history were the discovery of anaesthetics and the elucidation of the cause and the means of prevention of surgical sepsis. Surgical operations without anaesthetics were of course practised, but were so heartily dreaded that operation was not accepted by the patient until his condition was so bad as to be more distressing than the prospect of the knife and the probability of death, for gangrene and septicaemia made all operative mortality exceedingly high. Moreover the public demanded that the agony of an operation should be brief; so rapidity was the ideal of the eighteenth-century surgeon. Cheselden was famous as having performed a lithotomy in fifty-four seconds. The use of anaesthetics has rendered great speed of working useless: the surgeon's ideal to-day is infinite care and thoroughness. Before 1844 the only effective anaesthetic in use was alcohol, and a dose of alcohol sufficient to cause insensitiveness to pain was harmful to the patient's condition. Curiously enough, the anaesthetic effects of nitrous oxide (the "gas" of dentists) had been discovered in 1800 by Davy, who suggested its use in surgical operations, and the effects of ether were discovered in 1818; none the less the first practical application was not made until 1844, when Dr. Wells of Hartford, Connecticut, and Dr. Morton, a dentist of Boston, used ether vapour for causing anaesthesia in the extraction of teeth. The discovery was taken up at once in England. Sir J. Simpson tried ether in midwifery practice in 1847; in the same year he discovered the use of chloroform. It seems strange to recall that not a century ago, objection on moral

grounds was raised to the use of anaesthetics in childbirth, the pain thereof being considered to be a part of the curse of Eve.

These three substances, nitrous oxide, ether and chloroform, have remained the most important anaesthetics, though ninety years have passed and hundreds of others have been tried.

The invention of anaesthetics caused no great improvement in Surgery, which remained hopelessly fettered by sepsis. Every wound was expected to become purulent; a terribly high proportion of operations led to a general infection of the blood-stream and to death from pyaemia or septicaemia. The mortality from amputations often reached eighty per cent., and the maternal mortality in hospital practice sometimes reached comparable figures. No clue to the cause of the universal sepsis was to be found, and as it had always been a concomitant of surgical practice, it was not regarded with the horror we should accord it to-day.

Joseph Lister, born in 1827, took his medical degree in 1852. While still a house-surgeon he investigated cases of hospital gangrene and of pyaemia, and continued his researches at Edinburgh and at Glasgow, where he held the Chair of Surgery. It seemed at that date that any external wound, surgical or accidental, was almost certain to suppurate; this did not apply to internal injuries; the suppuration was, therefore, supposed to be due to the oxygen of the air. Lister became aware of Pasteur's work on putrefaction, and was led to suspect that sepsis and putrefaction were closely allied. Pasteur had shown the latter to be due to living germs in the air; Lister deduced that these might be the cause of sepsis. Air could not be excluded from the wounds, but living germs could be

killed. Granted that germs living and growing in a wound caused sepsis, the measures to be taken became clear to him. First of all gross contamination was to be excluded. Surgeons were using coats encrusted with old blood and pus; the same instruments were used on one patient after another without any cleaning; students and surgeons came straight from the post-mortem room to the operating theatre or maternity ward. If living germs were present in septic wounds and decomposing bodies, the surgeons were certainly distributing them most efficiently. In the second place, the air, as Pasteur had showed, contained germs of putrefaction, and these were present on any unsterilised material. Lister began in 1864 to use wound dressings impregnated with strong bacterial poisons such as carbolic acid; he sprayed dilute carbolic acid into the air and, most important of all, as it proved, he sterilised by heat or chemicals the dressings, the instruments and the surgeon's hands and outer garments. Gradually he came to see that the air-borne bacteria were not important, but that the essential factor in preventing sepsis was the absence of bacteria or their spores from hands, instruments and dressings. The antiseptic method, directed towards the killing of bacteria by poisons, thus gave way to the aseptic method, their exclusion from the wound.

The medical profession is conservative. Practitioners work out their own technique by years of experience and are loth to abandon it. Lister's teaching was but slowly taken up in England, though in Germany it was rapidly adopted. Yet the unheard-of success of his treatment compelled attention and in the 'eighties won general acceptance.

The consequence of the discovery of anaesthetics and

of aseptic surgery was the ability of the surgeon to conduct a long and careful operation on almost any part of the body. A tremendous development of surgical technique has ensued; it is only possible here to indicate a few of the headings of progress.

First may be placed the removal of sources of danger. Internal abscesses, which formerly gave rise to a general and usually fatal infection, are opened and drained: foreign bodies such as gall-stones or urinary calculi are readily extracted: organs whose functions are hopelessly deranged (e.g. varicose veins or a septic kidney) can be removed. Most important of all, malignant tumours, if diagnosed at an early stage, can be removed with a good prospect of non-recurrence; a great part of the progress of modern surgery is directed to the removal of malignant growths from less and less accessible positions.

Second comes the work of reconstruction, the repair of organs injured in accidents—bones, joints or viscera; the restoration of facial injuries by plastic surgery and the remedying of such congenital deformities as hare-lip or club-foot.

Third may be placed the assistance of natural processes, seen at its best in obstetric practice, where the once desperate remedy of Caesarean section is actually preferred by some mothers, in spite of its rather greater risk, to natural birth. In this place may be mentioned also the rise of dentistry which has done so much, not only to give comfort, but also to prolong life. Dentistry has been practised at least since 500 B.C. Tooth-drawing was performed, and from the eighteenth century onward very fair artificial teeth were made. The filling of teeth was adopted from an early date, but it was only in the 'nineties that the decay of teeth was recognised as bacterial in

origin. In the twentieth century the influence of oral sepsis on health has been widely recognised, and mouths full of untreated carious teeth are becoming as rare as they were once common.

NATURE AND CURE OF DISEASE SINCE 1850

The history of the progress of Medicine is largely the history of the understanding of the working of the body. In the eighteen-thirties human physiology was very little understood. Anatomy was well worked out; the organs were all known; but the physician had very little idea of what went on in them. To-day we know a great deal more, but we are still ignorant of a fundamental piece of knowledge, the way in which the changes in the cell—chemical, mechanical and electrical—are brought about.

The discovery of the connection between disease and bacteria has already been recounted. We have seen its effect upon preventive Medicine and Surgery. In the realm of Medicine this discovery caused a revolution. The identification of the bacteria causing the various diseases proceeded apace. The discovery of the streptococcus and staphylococcus by Pasteur in 1880, of the typhoid bacillus by Ebert in the same year, of the tubercle bacillus in 1882 and of the cholera vibrio in 1884, both by Koch, were incidents in a campaign of discovery not yet completed.

It was proved that infectious or contagious diseases are always caused by living agencies; these are of four main types. First are viruses, which consist of particles much smaller than bacteria and of which as yet little is known; smallpox and measles are familiar examples of virus

diseases. Second are bacteria. Third are protozoa, creatures of but a single cell but more highly organised than bacteria; they cause malaria, sleeping-sickness and some other tropical diseases. Last come higher parasites such as parasitic worms, which cause such conditions as trichiniasis, hookworm-infection, etc. The knowledge of the cause of such diseases at once paved the way towards prevention and cure. In 1889 it was discovered that normal blood has the power of destroying bacteria, and in the following year the formation of antitoxins was reported. These studies led to an understanding of the mechanism by which the body protects itself, producing substances which destroy bacteria and neutralise their poisons. The body could be provoked to produce these "anti-bodies" by a dose of the appropriate bacteria, dead or living, so becoming immune to the disease they cause; or animals could be immunised in this way and the serum of their blood containing the anti-bodies could be injected. Such methods cannot always be used; some acute diseases still have to run their course although the bacteria which cause them are known. A second line of attack is by chemo-therapy. It is a theoretical possibility to introduce into the blood-stream a drug which will poison the bacteria without injuring the host. This has but rarely been realised. However, Ehrlich's salvarsan and related drugs poison the treponema which causes syphilis, while the streptococcal affections such as erysipelas and puerperal fever have been cured by synthetic drugs of the sulphanilamide group. Many bacterial diseases, however, notably tuberculosis, can be cured only by the body's own resources; Medicine here has specialised in building up the body's powers by a suitable regime.

The non-infectious diseases are not in general caused

by parasites but by a derangement of bodily functions. Many of them remain a mystery. The causes of most of the forms of skin disease, heart affections, epilepsy, anaemias, etc., remain quite obscure. Medicine therefore can effect no radical cure. Cancer remains quite mysterious, though surgery or radium-treatment offers an excellent chance of recovery in early cases.

Two groups of non-bacterial disease, the hormonic diseases and the deficiency diseases, have yielded to medicine in recent years. From 1890 onwards the ductless glands received a good deal of study and it appeared that the thyroid, pituitary, parathyroids, the islets of Langerhans in the pancreas, the adrenals and the testes and ovaries, produce minute quantities of intensely active chemical substances, a lack or excess of which caused profound departures from normal function. Thus excess of thyroid secretion caused Graves' disease, a deficit of the same, cretinism or myxoedema; disease of the islets of Langerhans caused diabetes, and these, with other rarer diseases, can now be cured by a supply of the secretion if deficient, or if overabundant, by removal of part of the secreting organ.

From about 1911, it became apparent that food contained minute quantities of substances—vitamins—without which normal nutrition and bodily function could not continue, and to a lack of these, following on an unnatural or deficient diet, several important diseases were found to be due. Rickets, one of the commonest childish diseases, is now entirely curable by good food or sunlight: scurvy, pellagra and beri-beri are less well-known ailments which are curable and preventable by suitable diet.

Even now everyone has to die. But the average life-period of the new-born baby has increased in the last

century from about twenty to about fifty years. Our children are preserved from dying in early years from diphtheria, typhoid, smallpox and cholera; much fewer people die from tuberculosis and venereal disease. We are preserved to the age when we die of cancer, pneumonia, heart failure or a stroke. Not the least heartening feature of Medicine has been the prevention and cure of the diseases which carried off children and young men and women in their prime.

The study of mental disease is a highly conjectural department of Medicine, for the physical basis underlying mental disorder is largely unknown.

The eighteenth and early nineteenth centuries treated lunatics by crude and violent methods—beatings, drastic purges, and so forth. In the last quarter of the eighteenth century the hypnotic states induced by Mesmer aroused great interest, and the study of these during the nineteenth century laid a foundation for an understanding of abnormal states of mind. Hypnotic suggestion has proved valuable in the treatment of mental disorders, but the greatest advance was made by the workers who developed a technique for studying the workings of the unconscious mind. First among these is to be mentioned Sigmund Freud, whose method of dream-analysis and study of associations was developed from about 1900 onward. Jung and Adler developed other aspects of this analytical psychology. Like so many other theories, the "Freudian" psychology was pushed too far, but it is true to say that the modern technique of explaining mental disorder and devising treatment is largely based upon his work. The modern tendency is to treat accompanying physical ailments and to hope that returning health, removal from home surroundings, and the explanations and suggestions

of a physician, may aid the body and mind to re-establish the equilibrium of sanity.

DIAGNOSIS SINCE 1850

In no department of Medicine has there been more progress than in diagnosis—finding out the nature of the patient's disease. The old school of clinician depended on great skill in the interpretation of the patient's symptoms as perceived by the physician's eye and hand. This direct observation, while indispensable, has been supplemented by a great number of mechanical aids. From 1845 onward instruments began to be devised for inspecting various cavities of the body. By suitable arrangements of lights, lenses and mirrors, the retina of the eye, the larynx, the nose, the bronchial passages, the bladder, the rectum and the vagina can be inspected without anything resembling a surgical operation. In the last forty years the sense of sight has been further aided by the X-rays. The fact that these rays (p. 258), discovered in 1897, would traverse flesh much more easily than bone led almost at once to their use for making shadow pictures of bones, and thereby to a unthought-of degree of certainty in the detection and setting of broken bones. The extension of the use of X-rays to the photography of soft parts has followed. Organs give rather indistinct shadows, but it is often possible to introduce into them a substance which is opaque to X-rays and so obtain a good shadow. Thus a meal containing the inert and opaque barium sulphate will give a clear outline of the stomach or bowel containing it. Lipiodol, an oil containing iodine, may be introduced into the lung, so making the air passages opaque

to the rays. Other drugs (uroselectan) are excreted by the kidneys and give a clear picture of these and the ureters, while yet others may be injected into the blood and so enable the blood-vessels to be photographed.

Two other new means of diagnosis are of the highest importance. A specimen of blood or other body-fluid can be incubated on a suitable medium and the bacteria in it cultivated. In this way consumption, diphtheria, scarlatina, etc., may be diagnosed with certainty in a day or so. Again a small portion of tissue may be removed, cut into microscopic sections and examined. The cancer-cell is readily distinguished under the microscope from the healthy cell, and in this way malignant tumours may be detected and excised before they have invaded the body widely.

Finally a number of important special tests may be briefly mentioned. The action of the heart, which is but rudely indicated by the stethoscope, can be mapped out exactly by a tracing of the minute electric currents engendered by its action. Blood pressure is measured as routine test. Chemical tests for urea and sugar in the blood and urine, the testing of the rate of working of the body by measuring the oxygen used per minute, examination of the nervous system by the testing of reflexes, counting of the various types of cell in the blood, can only receive a mention here.

ASTRONOMY SINCE 1850

The advance in Astronomy since the year 1850 has taken three chief courses. In 1850 our knowledge of the real, as opposed to the apparent sizes and positions of

the heavenly bodies was almost confined to the solar system. Since that time there has been, first, a greatly increased knowledge of the positions and motions of the stars and nebulae; secondly, an increased understanding of the nature and structure of sun and stars; thirdly, more probable conjectures as to the evolution of the heavenly bodies. A great part of these discoveries has arisen from two new and powerful aids to astronomical observation —the spectroscope and the photographic plate.

As a result of increasing perfection of instruments a vast number of new heavenly bodies have been recorded. In the solar system, several new satellites and some hundreds of asteroids have been discovered and in 1930 the small tenth planet Pluto, far beyond the orbit of Neptune, was added to the solar family.

The ancient task of mapping and cataloguing the stars has continued at a vastly increased pace owing to the aid of photography, which was enlisted by Sir David Gill in 1885. There are now some 2,000,000 stars catalogued. The nebulae have been discovered in very great numbers, particularly in this century, after it was realised that the majority of these were island-universes comparable in size with our whole local system of stars.

Even more enlightening than the discovery of new bodies has been the measurement of the distances and of the proper notions of the stars. Up to about 1840 the stars could only be studied as moving points on a hypothetical sphere; to-day we can construct an approximate scale model of the universe within the range of our telescopes. The mapping of distances of stars started by the classical trigonometrical methods. The nearer stars appear to shift relatively to the further ones as the earth moves round its orbit. This shift is very small, but in

1838 the first stellar distance was calculated in this way, and by 1910 the distances of some seventy or eighty stars had been thus worked out. The distance of only the nearest stars can be determined in this way, but of recent years two powerful means of finding the distance of very remote objects have been discovered. Roughly speaking, it has been found that all stars with identical spectra have about the same luminosity, so that the apparent brightness of a star of a particular type depends in a calculable way upon its distance. This is obviously applicable only to single stars bright enough to give a spectrum which can be observed. The second method is even more effective. The distance of even the most distant nebulae can be discovered if there can be seen in them a peculiar type of pulsating star—the Cepheid variable. The true brightness of this depends on its period of pulsation, which is readily observed. Its apparent brightness is then determined and its distance can thus be worked out. This method arises from the work of Leavitt; Hertzsprung and Shapley between 1908 and 1918 have gone far to clear up the problem of the dimensions of the universe. The cosmos within the range of our telescopes now appears as a system of gigantic flattened discs each containing millions of stars, discs some fifty thousand light-years in diameter and an average of a million or so light-years from each other.

The question of the motion of the stars has been worked out with much care. From the seventeenth century it had become apparent that some stars had shifted relatively to others. Telescopic observations could only give the transverse motion, for motions to or from the observer cause no apparent shift in position. In 1842 Doppler enunciated his principle that the light emitted from an

object receding from an observer should appear of lower frequency and the light from an object approaching the observer should appear of higher frequency than the light from the same object when stationary. Sir William Huggins in 1868 applied this principle to stars, and found that the spectral lines of some were shifted towards the red and others towards the blue. The former were therefore receding from and the latter approaching the earth at speeds which could be calculated. It was therefore possible to observe and combine the transverse and the line-of-sight velocity of the stars and to find out how they were moving. In 1904 Kapteyn examined these motions and found the stars were drifting in two main streams. Since that time there has been advanced much evidence that our whole galactic system or local universe is rotating like a gigantic wheel. The motions of the island universes outside our system have recently been observed on the Doppler principle by Slipher and others and they appear to be receding from each other at gigantic speeds. The universe appears to be expanding.

The mass of the stars has been measured by observations on binaries, pairs of stars which rotate round each others. Some fifteen thousand pairs have been observed, and in sixty or seventy cases the orbits can be mapped out clearly enough for the calculations of the masses. It appears that the masses of the stars do not differ very greatly from that of the sun.

The sizes of the stars have also been worked out. Though none gives a measurable disc even at the highest magnification, yet an optical method of measurement from interference fringes, suggested by Fizeau in 1868 and developed by Michelson (1920), has made this possible. Stars vary enormously in size but very little in

mass. At one extreme are dwarf stars such as the companion of Sirius, nearly as heavy as the sun but not as large as Uranus, and having the incredible density of *c.* 60,000: at the other extreme are the gigantic stars like Betelgeuse, large enough to fill the whole orbit of Mars and having a density less than a hundredth of that of ordinary air.

The spectrum of the sun was studied at the beginning of the nineteenth century by Fraunhofer (1814–15). A few of the characteristic lines were identified, but real progress began only in 1859 when Kirchhoff showed that the dark lines in the solar spectrum were due to the absorption of light by the sun's atmosphere and were to be found in the same position as the corresponding bright lines in flame spectra. It was soon shown that the sun contained many of the familiar terrestrial elements and observation of the spectra of the sun and stars has not indicated the presence in them of any element not now known on earth. The observation of the spectra of stars followed at once on that of the sun, and it was found by Secchi (1862) that the different stars gave spectra of different types and a classification of stars on this basis has proved of great value. From 1888 photography has been employed.

The spectra of stars give us information of many kinds. They tell us what chemical elements are present in them, the approximate temperature of the surface of the star, and whether it is approaching us or receding from us.

In the last twenty years much progress has been made towards a credible theory of the origin, development and ultimate fate of the universe. Laplace's hypothesis (pp. 194–5) was throughout the nineteenth century held to be a possible but unproven view of the way in which

the solar system might have been formed. Little attention was paid to investigating the life-history of stars, as a matter not open to observation. The principle of the conservation of energy and the detailed study of radiation made it clear that the sun and stars were emitting energy at a great rate. It appeared that if they were merely hot bodies cooling their period of emission of radiation could only be of the order of ten to one hundred million years. These views, expressed by Kelvin and others, conflicted with the biologists' estimate of the time needed for the deposition of strata and for evolution of species, which it seemed might require a life for the earth many times greater than the physicists could allow for its parent the sun. The discovery, at the beginning of the present century, of the radioactive elements, which continually emit energy, lengthened the estimate, but not sufficiently. In the twentieth century new light was thrown on the matter. In the first place evidence, both theoretical and practical, showed that mass could be converted into energy, and that the stars, by converting a part of their mass into energy, might continue to radiate for billions of years. Secondly the newly-acquired knowledge of the constitution of the atoms of which the universe is built up (p. 241) enabled Jeans, Eddington and others to predict the probable effect of the vast internal temperature of the stars on the matter of which they are composed and to build up a theory of their evolution. The present view of the history of the universe may be very briefly set out as follows: it should be remembered, however, that it rests on a great deal of conjecture and will certainly be modified as our knowledge increases.

J. H. Jeans visualises the universe as taking its origin from a gigantic cloud of exceedingly rarefied gas more

attenuated than any earthly attempt at a vacuum. Such a gas would condense by the action of gravity into huge clouds comparable in size with our galactic system. The cloud would become a sphere: the attraction of other clouds would cause it to rotate. Gravitational forces would cause it to contract; this would quicken its rotation so that it would become flattened and lens-like. Matter would be flung off from its edges and would condense into stars. The theory of the evolution of stars is largely due to A. S. Eddington. The stars as flung off would at first be vast tenuous clouds of glowing gas like the giant stars; as they contracted by gravitational forces they would become hotter and finally reach a temperature of some 20,000,000° C. in the centre.

It seems from their spectra that the giant stars contain a great deal of the lighter elements such as hydrogen. This at the high temperature and pressure of the interior of a star, would, it is believed, be built up into the nuclei of heavier elements, losing mass in doing so, which mass would appear as radiation.

It was formerly thought that a rotating star could cast off planets in consequence of its rapid rotation, but it is now evident from the work of G. H. Darwin (1900) on tidal forces and the researches of Jeans that the result would be the splitting into a double star. Jeans' theory is that the near approach of another star to the sun drew out from it a long filament of gaseous matter which liquefied and split up into planets which in turn ejected their satellites.

Such theories as these are, of course, tentative, but are on a sounder foundation than the older cosmogonies because we now know more about the sizes and masses of stars and the laws governing matter under the conditions prevailing therein.

The theory of relativity developed by Einstein and further elaborated by Eddington and others during the last twenty-five years, has profoundly modified the scientific outlook, though it is not easy to point to any great scientific advance as being primarily due to it. The theory of relativity is essentially the combination of Time and Space within a single concept. By its aid events can be described in a way which presents true information to any observer whatever his position or velocity: this gives an aesthetic satisfaction to the man of Science who has the mathematical equipment to use it. The modifications in which the theory of relativity requires to be made in our "classical" laws of Nature are negligible, except where enormous velocities or concentrations of forces are concerned. It therefore finds its chief importance in the physics of the atoms and stars and has no great importance to our large-scale terrestrial phenomena, the forces concerned in which are but feeble. The notion that mass and energy are interconvertible is of the first importance. The theory of relativity is felt to be significant, not because of its practical fruits, but because it provides a mode of thought in which the great concepts of time, space, mass, gravitation, energy and inertia are seen as aspects of a single world-conception.

THE MECHANISED WORLD

The Industrial Revolution of the early nineteenth century is striking as being the process which initiated our modern industrial civilisation. We are, perhaps, apt to overlook the fact that industrialisation has proceeded at an ever-increasing pace since that period and has never

been more rapid than in the decade following the war of 1914–18. In 1850 the railway and steamship industries were in active and increasing prosperity, but the great mass of commodities, other than textiles, was made by the old craftsman's methods. The story of the last eighty years of industry is the substitution of the machine-minder for the craftsman. The use of machinery for textiles and engines required the development of more accurate and elaborate machine tools; these in turn made it possible to make ever more elaborate pieces of mechanism. The substitution of steel for iron as the result of the new processes discovered by Bessemer (1856) and the brothers Siemens (1866) greatly aided the process. The development of the electrical industries from 1880 onward and the motor-car and aeroplane industries from about 1900 and 1910, respectively, caused a great development in the production of elaborate and precise machinery. The consequence of this has been that it has in recent years become profitable to construct elaborate machinery to perform all industrial operations, if thereby fewer or less-skilled workers per unit of production can be employed. The consequence has been a great increase of production by each person employed. Between 1899 and 1925 the population of the U.S.A. increased by seventy per cent. The volume of production increased by one hundred and seventy-five per cent and the volume of production per worker by 50 per cent. The world has not found it easy to adjust itself to this increased power of production.

The results of the growth of the machine are profound. We can find almost nothing made on the large-scale in the twentieth century which is not the product of elaborate machinery. The lives of every townsman and, though to a less extent, of every countryman, have been completely

transformed. The mobility of man is now only limited by his pocket. Bombay and New York are only a few days apart by air, and, more important for most of us, the most remote country village in England is not ninety minutes' journey from a city. The population is tending to live in an urbanised countryside and to amuse itself in the towns. The electrification of industry has greatly aided this by taking power from the crowded coal-districts to factories in areas not previously industrial.

Our leisure is largely mechanised, and this represents perhaps, the profoundest of the influences of science upon us. We amuse ourselves by going somewhere in an automobile, by visiting a cinema, or by listening to a gramophone or radio. All these cost money, and serve thereby to bind us closer to the industrial civilisation. We have far more goods. Every woman can buy charming clothes of artificial silk—made from wood-pulp: her *lingerie* challenges comparison with that of a Victorian princess.

But in doing all this we have created for humanity an environment wholly remote from the ancient stable agricultural community. The modern industrial civilisation is a complex machine depending on co-operation of a vast number of persons who are very imperfectly aware of the function they are performing, and may be quite indifferent to the welfare of any but themselves. The social structure may collapse, and I do not see why we should greatly regret its loss; the scientific knowledge which has built it up, is, however, unlikely to disappear unless, as has happened before, the human mind has its interests diverted into some new channel.

THE SPIRIT OF SCIENCE

The conflict of Science and Authority ended with the Evolutionary Controversy in the 'seventies. Since that time the scientific method of objective observation, experiment and statistical examination has invaded every department of knowledge. Whatever has to be investigated to-day, is investigated by the scientific method, no matter whether the subject is the mental processes of animals, the optimum conditions for growing beetroot, or the type of chocolate preferred by insurance clerks. A century ago, the approach to these subjects, insofar as they would have commended themselves as matter for investigation at all, would have been the construction of a theory on more or less *a priori* grounds supported by a few well-known facts. To-day the tendency is to discard theory and to collect and classify great numbers of instances and obtain from them some statistical rules.

The powers and limitations of science are becoming progressively more clearly realised. The scientific method is regarded as the only means of dealing with facts, but we are more ready to realise that the results yielded by scientific reasoning are but products of the human mind. The world of science is an intelligible and self-consistent view of the universe, but its intelligibility is due to the fact that we exclude from science all data which are not expressible in terms of mass, length and time. Its consistency and the appearance of a great Order of Nature may be due, as Eddington believes, to the logical processes by which our minds have constructed the scientific edifice.

Nevertheless, it works. By the aid of science we can

control matter and energy, and for the purposes of matter and energy, science is the sole truth. There is another world of sensation, beauty, and intuition, insusceptible to logic. To this world science seems inimical. In this Age of Science, the arts of poetry, music, sculpture and painting and architecture have increased in output and diminished in value. Could we but have the health, security, leisure and comfort of to-day and the intense life and inspiration of ancient Greece or the Renaissance —there were a world fit for men.

SUGGESTIONS FOR FURTHER READING

The following is a brief and perhaps arbitrary selection of recent books in English dealing with the history of the individual sciences.

A History of Astronomy. W. W. Bryant. 1907.

A Short History of Biology. C. Singer. 1931.

A Short History of Chemistry. J. R. Partington. 1937.

A History of Mathematics. F. Cajori. 1919.

A Short History of Medicine. C. Singer. 1928.

A History of Physics. F. Cajori. 1929.

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SUBJECT INDEX